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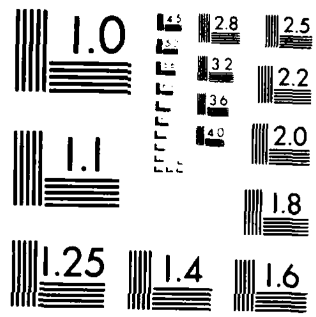

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report summarizes the recent activities and results of a study seeking to discover and quantify the relationship between solar wind parameters, magnetosheath turbulence, and daytime geomagnetic pulsations. The most significant achievement has been a major advance in data processing and computational analysis leading to the first observations and measurements of magnetospheric resonance thickness, wave transfer across the magnetopause, and wave structure in the outer magnetosheath.

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FINAL REPORT OF

A PROJECT TO DEVELOP AN INDEX OF PC 3, 4, 5 GEOMAGNETIC PULSATIONS AND TO STUDY THEIR CONTROL BY SOLAR WIND PARAMETERS

Prepared for

Air Force Office of Scientific Research
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April 1983

<u>Principal Investigator:</u>

Eugene W. Greenstadt
Space Sciences Department
Bldg R-1, Rm 1176
TRW Space and Technology
Redondo Beach, California 90278
(213) 536-2015

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ABSTRACT

This report summarizes the recent activities and results of a study seeking to discover and quantify the relationship between solar wind parameters, magnetosheath turbulence, and daytime geomagnetic pulsations. The most significant achievement has been a major advance in data processing and computational analysis leading to the first observations and measurements of magnetospheric resonance thickness, wave transfer across the magnetopause, and wave structure in the outer magnetosheath.

1.0 INTRODUCTION

This report summaries the currently terminating phase of the TRW study of medium-period, daytime geomagnetic pulsations. The study is aimed at development of an index or measure of pulsation activity by examining the pattern of pulsation activity on the ground and the generation or control of pulsation signals by conditions in the interaction region between the solar wind and the magnetosphere. In previous programs it was determined that pulsation properties can be related to certain solar wind parameters in a manner consistent with models predicting excitation of magnetospheric waves at the magnetopause. We have been moving toward defining and quantifying the global effects of the solar wind control of magnetospheric pulsations.

The pulsations of concern here consist of small-amplitude, quasi-sinusoidal wavetrains from several cycles to hundreds of cycles long, detected by sensitive instruments measuring the magnetic field (or earth currents) on the earth's surface. These pulsations are signals traditionally designated Pc 3, Pc 4, and Pc 5, covering the period (frequency) ranges 10-45 (.022-.1) , 45-150 (.0067-.022), and 150-300 seconds (.0033-.0067Hz), respectively. There is reason to believe that in these period bands, phenomena can be quantitatively related to the solar wind with sufficient reliability to make them useful as diagnostics of selected solar wind properties.

The intermittent excitation of specific micropulsations, whose period at any given time is related to resonant properties of the magnetosphere, is probably the result of solar wind interaction with the magnetopause. Qualitative models exist that provide mechanisms for delivery of the magnetosheath oscillations to the magnetopause or for local excitations at the magnetopause irregularly in a manner potentially consistent with the known characteristics of Pc 3,4,5. The mechanisms, in turn, depend upon intermittent properties of the interplanetary magnetic field (IMF) and the solar wind velocity which have been shown to correlate with micropulsation amplitude. The objective of this study is to improve and quantify the existing correlations and deepen the understanding of the entire solar wind-to-surface transmission process.

In the ensuing sections we list the tasks accomplished and results achieved in the study interval ending February 1983, and summarize the principal results, appending completed abstracts and reports where appropriate.

2.0 ACTIVITIES

The following list summarizes the individually definable activities carried out under this program.

2.1 Pc 5 Investigation

Event identification

Data retrieval, plotting, and frame transformation

Definition of environmental context

Spectral analysis

Report preparation, IAGA (Edinburgh)

Report preparation, AGU (San Francisco)

Draft paper

2.2 Pc 3,4 Investigation

Straddle search and event identification (see 3.4, below)

Creation of flat files

Interactive spectral analysis

Visit to AFGL

Report preparation (AGU Chapman Conf., Kona)

Write paper

2.3 Meetings Attended

IAGA, Edinburgh, August 1981

AGU, San Francisco, December 1981

COSPAR and IMS Symposium, Ottawa, June 1982

AFGL Discussions and Data Analysis, Lexington, June 1982

AGU, San Francisco, December 1982

AGU Chapman Conf. on Waves in Magnetospheric Plasmas, Kona (Hawaii), February 1983

2.4 Related Activities

ISEE Science Working Team, meeting at NASA/GSFC, February 1982

NASA/Data Science Users Working Group, meeting at NASA/MSFC, October 1982

Quasi-Parallel Shock Correlation-Length Study

2.5 Reports for Publication

Large-Amplitude Magnetic Variations in Quasi-Parallel Shocks: Correlation Lengths Measured by ISEE 1 and 2: E. W. Greenstadt, M. M. Hoppe, and C. T. Russell, Geophys. Res. Lett., 9, 781, 1982

Transfer of Pulsation-Related Wave Activity Across the Magnetopause: Observations of Corresponding Spectra by ISEE-1 and ISEE-2: E. W. Greenstadt, M. M. Mellott, R. L. McPherron, C. T. Russell, H. J. Singer, and D. J. Knecht, Geophys. Res. Lett., submitted, 1983

A Storm-Time, Pc5 Event Observed in the Outer Magnetosphere by ISEE 1 and 2: Wave Properties: E. W. Greenstadt, R. L. McPherron, M. M. Mellott, R. R. Anderson, and F. L. Scarf, J. Geophys. Res., to be completed, 1983

3.0 RESULTS

The following list emphasizes the most significant, specific accomplishments and results of this program during the interval on which we report.

Pc 5 Investigation

Spectral profile of inbound, dusk meridian-pass through the magnetosphere during wave event;

Two-point (ISEE-1,2) profile of the Pc 5 resonance region;

Measurement of resonance region thickness of ~.4 Re.

Pc 3,4 Investigation

Comparison of power spectra straddling the magnetopause;

One to three order attenuation of power across the magnetopause;

Relative stability of spectral power deep in the magnetosphere;

Correlation of power level across the magnetopause;

Spectral similarity across the magnetopause.

Shock Source Investigation

Correlation length of quasi-parallel, large-amplitude waves ~1000 km.

The remainder of this Section explains and describes the most important aspects of the project.

3.1 Technical Considerations

Our flexibility in selecting various aspects of pulsation phenomena for investigation has allowed us to make significant progress, sometimes in spite of, sometimes because of, technical developments. We took the position from the outset that it would be neither practical nor supportable for TRW's Space Sciences Department to duplicate sophistocated interactive data analysis codes available or under development at UCLA (Berchem and Russell 1982; see also Appendix C) where portions of our satellite-data base are located. Our project has therefore been depended on progress elsewhere in writing certain routines and bringing on-line associated equipment outside the investigator's direct control. The difficulty has been compounded by our desire to employ data from the still more distant data base of the AFGL magnetometer network, because we believe the AFGL stations to be ideally situated for Pc 3-4 studies. The impact of these obstacles can be appreciated by reference to the graph in Figure 1 of investigator hours charged to this contract; charges followed a uniform straight-line time budget for the initial effort on the Pc5 study until October 1981, then fell into deficit until August 1982 (shading) as we awaited debugging of new routines and expansion of temporary working disc-space at UCLA. Our effort accelerated after July 1982 as we began to explore "straddle" cases (paragraph 3.4) which are still actively under analysis as this is written.

3.2 Pulsation Index

The foremost victim of our technical problems was the objective of devising some sort of "global" Pc index, because of the large working file-space required to analyze data needed to produce a reliable outcome. This part of the project was initiated, however, with AFGL data sent by H. J. Singer and D. J. Knecht in support of our straddle cases described later. We note with appreciation that the AFGL cooperation was responsive and quite rapid.

One aspect of the index problem is a need to determine the relationship between traditional Pc signals on the ground and in the magnetosphere above the ionosphere. So far, we have found relatively little difference in spectral power between the outer magnetosphere and one of the AFGL stations. (see 3.4, below).

3.3 Dusk Pc 5 Events

Our initial study of the events detected by ISEE-1 and -2 inbound through the magnetosphere on August-1978 yielded a magnetic profile of the event reported at the IAGA meeting in Edinburgh last year. For the most part, the profile confirmed the similarity of our event to others described earlier, but did not add much new, outside of the correlation between the two spacecraft records. Improved technical capability has recently enabled us to proceed further.

Figure 2 is a hard copy of a computer working-plot showing the principal Pc 5 event, band-filtered and transformed into field-aligned coordinates where the z-axis is in the direction of the Earth's main field. The vertical lines are cursors set on the peaks of the compressional (Bz) component; they serve here as guidelines to the phase relationships of the transverse components. We see that at the asterisk the x- and y-components were in opposite phase. Before that, Bx led By; afterward, Bx lagged By. The in-phase, linear polarization at the time of the asterisk coincided with the maximal amplitude of the transverse component $B_\perp = (B^2_r + B_\phi{}^2)^{1/2}$ not shown, as well as the compressional component, B_z. The entire sequence corresponds exactly to the behavior of the perturbation expected when crossing a magnetospheric field-line resonance (Chen and Hasegawa, 1974) and inferred from the only earlier comparable measurements by Hedgecock (1976). The phase reversal of the observed waves is represented sharply in another way in Figure 3, where the cumulative angle of rotation of the transverse field vector is plotted vs. time for both ISEE-1 and ISEE-2. We see the angle rose in both records until resonance after 0030, and fell therafter, indicating the reversal of the vector's rotation at the same time the vector's magnitude peaked. Even the delay between the phase reversals at the two spacecraft is apparent in the figure.

These figures offer the first documentation of a resonance, in place, in so clear and comprehensive a manner. The most interesting new inference to be obtained from the example, however, is the radial thickness of the resonance shell, a quantity hitherto not well determined (Hughes, 1980). We have for the first time a direct measurement of the thickness from the time over which the transverse components underwent a 180 deg. phase shift, indicated in the figure by the arrows. The marked interval corresponds to a distance of about 2500km.

The plots of Figure 2 and the thickness estimate above are derived from ISEE-1 data alone. The thickness can be estimated independently by comparing the data from ISEE-1 and ISEE-2, and a full characterization of the wave event can be obtained by intensive analysis of the signals in the two data records. We have measured the power of all components, their ratios, and phases in each data stream and cross-correlated these quantities between the two data streams. We expect to derive all wave properties for the linearly polarized waves in the outer magnetosphere as well as the plasmapause wave event, and then to compare the results with properties derivable independently by reference to plasma and electric field measurements available from the same spacecraft. One outcome will be a further test of the plasma and field relations of resonant standing waves, relations which have been depended on in the past to infer wave properties (Singer and Kivelson, 1979). A second outcome will, we hope, be a clarification of the way in which both the lower and higher harmonics, observed on the same pass, were related to position in the magnetosphere.

A progress report on this work was presented to the December 1982 AGU meeting; a copy of the Abstract appears here as Appendix A; the first of two papers describing the results is almost completed, a draft of which appears as Appendix B. A second report is planned describing the remaining physical properties of the waves. Comprehensive ion, electron, and electric field data accompanying the wave event have been collected or requested with the intention of enabling us to describe completely the Poynting vector, harmonics, and origin of storm-time, dusk meridian, plasmapause phenomena of which our event seems to be such as outstanding example. Our results will supplement other recent inquiries (Poulter 1982; Young et al, 1981, Mauk et al, 1981, Roux et al, 1982).

3.4 Magnetopause Straddles

Establishment of a direct Pc link to the solar wind will depend sooner or later on an actual observation somewhere of wave energy in process of transfer from outside to inside the magnetosphere. With the idea that "somewhere" might be, at least occasionally, where the ISEE-1,-2 satellites were, we searched the data for magnetopause "straddles", i.e. crossings where the two satellites were simultaneously on opposite sides of the boundary long enough (> 20 minutes) for reliable spectra to be computed. We also sought a subset of cases in which one or more of the AFGL stations was in the daylight hemisphere, preferably in or near the meridian of the spacecraft when they were at the magnetopause. As usual in such studies, the number of cases satisfying all the selection criteria was small, and analysis has barely started as this is written.

The results so far are very encouraging. The center of Figure 4 displays plots of field magnitude from ISEE-1 and -2, surrounded by various spectra, for the magnetopause straddle of 8 October 1978, as follows: ISEE-2, lower panel, entered the magnetosphere first at 1805:50 and finally at 1813; ISEE-1 encountered the magnetosphere first at 1831 and entered finally at 1835:40. Thus, there were 18 minutes during which data were acquired simultaneously from one satellite outside and one inside the magnetopause.

Spectrum A1 at upper left shows the wave power in the total field in the magnetosheath just outside the magnetopause, at ISEE-1. The leftmost spectrum below the field plots, B1, shows the wave power in the magnetosphere just inside the magnetopause, at ISEE-2, for the same time interval as that of the first spectrum. The power was appreciably lower and the decrease in power with frequency clearly much steeper inside than outside the magnetopause, beginning with about one third the outside power at the lowest frequencies. At 0.1 Hz, there were three orders of magnitude difference between the two spectra.

Spectrum A2 at upper right represents the wave noise just inside the magnetopause, this time at ISEE-1 after it crossed the boundary. The spectrum shows the same general reduction in power and steep decline with frequency seen at ISEE-2 in the same locations, although the shapes of the two post-crossing spectra are not identical. Spectrum B2 from ISEE-2 concurrent with this post-crossing ISEE-1 spectrum is further inside the magnetosphere; we see that the noise power is still lower at the upper frequencies, reducing the overall slope of the curve.

Finally, spectra G1, G2, at bottom, represents the power on the ground at the AFGL station at Newport, Washington, for the same intervals as in the depicted satellite samples. The ground station and the satellites were both at the same approximate local time, about 1300 LT, i.e., in the early afternoon. With the exception of G1, all the spectra show a concentration of power between .02 and .07 Hz in the form of a plateau or peak in the respective curves. This range of frequencies has been shaded in all the spectra of the figure.

Superposition of the A1, B1, G1 spectra of Figure 4, illustrated at the left of Figure 2 in Appendix D, shows a progressive decline in power from the magnetosheath to the earth's surface, Each spectral curve is contained in, i.e. accounts for a fraction of the power of, the next spectrum further up. The magnetospheric spectra are well below that of the magnetosheath and are closer to one another than to the latter, the discrepancy being greatest at the highest frequencies.

While we would not describe spectrum A as showing much of a "peak" between .02 and .07 Hz, we might describe the sheath power as somewhat "enriched" in that range; certainly there is discernible change in spectral index at or a little below .04 Hz.

The superposed spectra give the impression that wave power dropped rapidly and radically with distance from the magnetopause, at all covered frequencies, but selectively retained a peak of enhanced power just about where the apparent "enrichment" of the magnetosheath power occured.

Figure 2 of Appendix D, right hand side, superposes three spectra from the second case when ISEE-1 was outside the magnetopause, ISEE-2 was inside the magnetosphere, and the Newport station was below and east of the satellite meridian (in the early afternoon sector). In this instance, the power in the sheath (A) displayed enhancement and a plateau between .011 and .5 Hz, as did also the power in the magnetosphere (B), while the corresponding power on the ground (G) was relatively featureless.

Whether the apparent lack of response on the ground in (G) was because of a delayed effect not yet visible, an unfavorable position in the afternoon sector, or a poor choice of representation of the surface record is still to be determined. The inserted spectrum just below shows the power distribution in By at newport for a two hour interval including the 22 minute segment of the upper graph; clearly, there was some activity in the surface field within the longer interval and within the enhanced portion of the spectrum at the satellite.

One possible explanation for a variable responsiveness of magnetosphere might be, as we would hope, a variable condition of the solar wind. An indication that this was the case is illustrated in Figure 5. The field plots for 27 November are at the top; immediately below is a plot of the cone angle of the IMF measured by ISEE-3 some 200 Re upstream of the earth, but with the time axis shifted half an hour to allow for the approximate solar wind delay from ISEE-3 to the earth. The sequence of small panels at the bottom shows the power spectra inside the magnetosphere at ISEE-2. We see that activity in the spectra between 0.01 and 0.1 Hz varied according to whether the cone angle was favorable or unfavorable to quasi-parallel shock structure in the subsolar magnetosheath, i.e. whether the graph is shaded or not: favorable means the cone angle was within 50° of 0 or 180°. This relationship appears to have been independent of the visible turbulence in the magnetosheath field at ISEE-1, which would be a contradiction. Quasi-parallel turbulence should be largely transverse, however, and the waves in the sheath were mostly compressional before 2100 and mostly transverse after 2100. Thus the correlation of spectral enhancement with favorable cone angle may be the important factor here.

Although the pattern of the power curves in Figure 2 of Appendix C differ from each other, the order of descent in overall magnitude is the same. For the moment, we may offer the generalization that the decade of frequency between .01 and .1 Hz was enhanced in both our cases in some manner in all spectra examined so far, but that spectral peaks varied with time and position in a way that matched magnetosheath to magnetosphere on the two different days.

We interpret the figures as the first presentation of direct observations compatible with the proposition that magnetospheric field variations in the Pc 3-4 range are derived from field variations in the magnetosheath. The frequency band .02 to .055 Hz corresponds to the period range T=18 to 50 seconds spanning the traditional division (at 45 seconds) betweenPc3 and Pc4.

We do not assert at this stage that transfer of Pc3-4 power across the magnetopause has been directly demonstrated, but we see that minimal conditions for transfer were certainly present. The number and, more importantly, the variety of supportive cases is still too small to be conclusive. What the cases developed so far do is beg a set of questions that sharpen inquiry and narrow the path of future investigation.

An abstract (Appendix C) summarizing the results so far was submitted to the Chapman Conference on Waves in Magnetospheric Plasmas held February 1983. A very condensed summary of the early material has been submitted to a special issue of GRL on this conference; it is attached as Appendix D. A second report describing the cone angle effect is in preparation.

3.5 Quasi-Parallel Correlation Lengths

In attempting to trace the origin of daytime geomagnetic pulsations to the magnetosheath and/or the shock, we must ultimately concern ourselves with local properties and scale lengths of the disturbed plasma that impinges on the magnetopause. For the most part, the magnetosheath is unknown territory, the exceptions being its overall spectral behavior and the variability of that behavior both spatially and temporally. We began to study the wave scale characteristics of the magnetosheath by performing cross-correlations of the magnetic signatures of the large-amplitude waves of the quasi-parallel bow shock, using data obtained by ISEE-1 and ISEE-2 in the wave region during an extended interval when the two spacecraft were at different distances from each other, but including the largest separations recorded so far. We found that the similarity of signals at the spacecraft fell off rapidly as their distance approached 1000 km., a figure comparable to the average Larmore radii of the heated, secondary ions invariably associated with quasi-parallel shock structure.

Appendix E is a copy of a reprint of the published result. The implications for excitation of magnetospheric pulsations will become clear, we hope, when we extend our analysis to a similar study of waves in the magnetosheath itself. We expect such correlation lengths to be related to the uniformity, or lack thereof, with which the dayside magnetopause surface might be stimulated by sheath turbulence.

4.0 RECOMMENDATIONS

We cannot disguise our enthusiasm for the recommendation that every aspect of pulsation analysis be pursued further along the lines we have discussed. The objective basis for our advice consists of two pivotal facts:

1. The computational tools, consisting of both hardware and software, are substantially developed for advanced, interactive, quantitative analysis of both magnetic and electric signals in satellite and ground station records. Even charged particle data can now be subjected to the same processing whenever available in the appropriate form. None of this could be asserted two years ago. Indeed, substantial progress toward these capabilities has been made within the scope of this study, and related projects, both at TRW, UCLA, and elsewhere are continuing on ever more sophistocated levels as this is written.

2. There is now widespread interest and acceptance of the concepts and results regarding an exogenic source of Pc 3,4 pulsations in foreshock signals, shock pulsations, and magnetosheath turbulence, and several groups are actively examining this phenomenon in statistical and case-by-case studies.

We believe that the happy combination of circumstances enumerated above will shortly inaugurate the interval of high productivity, mutual stimulation, and rapid advance that usually follows such developments, and we urge that the following features of Pc 3,4 activity be pursued:

Power drop across the magnetopause as function of position, time, and ambient parameters;

Dependence of power on position in the magnetosphere;

Power pattern in the magnetosheath;

We do not discount the time, effort, and resources still required to characterize any global process of the magnetosphere, but we are optimistic that correlation of the results of such studies with the pattern of daytime power at AFGL (and other) stations on the earth's surface will contribute, and lead directly, to an index of surface pulsations as monitor of conditions outside the magnetosphere and should contribute much of the foundation for describing the transfer function of the magnetosphere, at least within the frequency band of Pc 3 and 4 pulsations.

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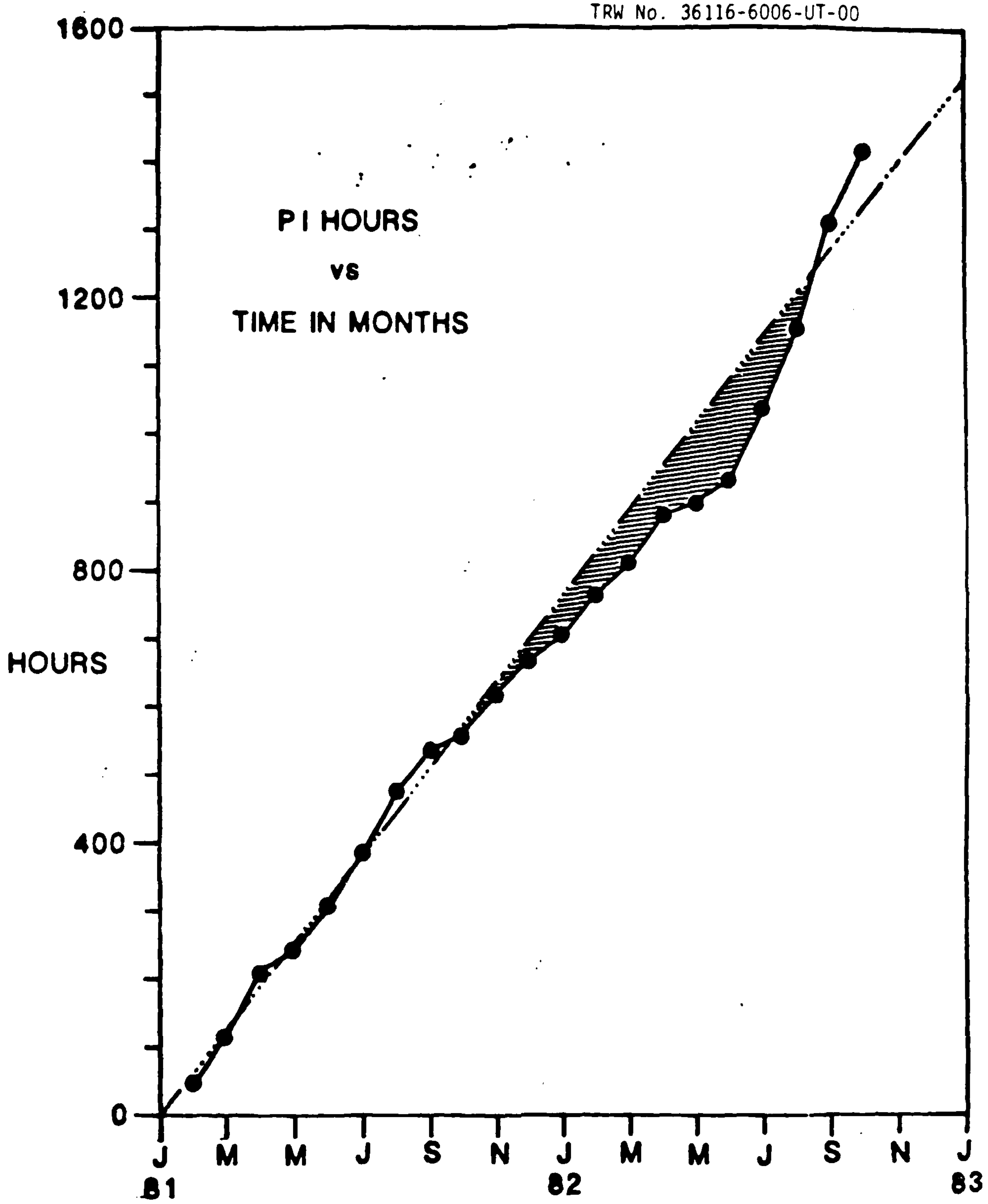

Figure 1. History of principal investigator hours

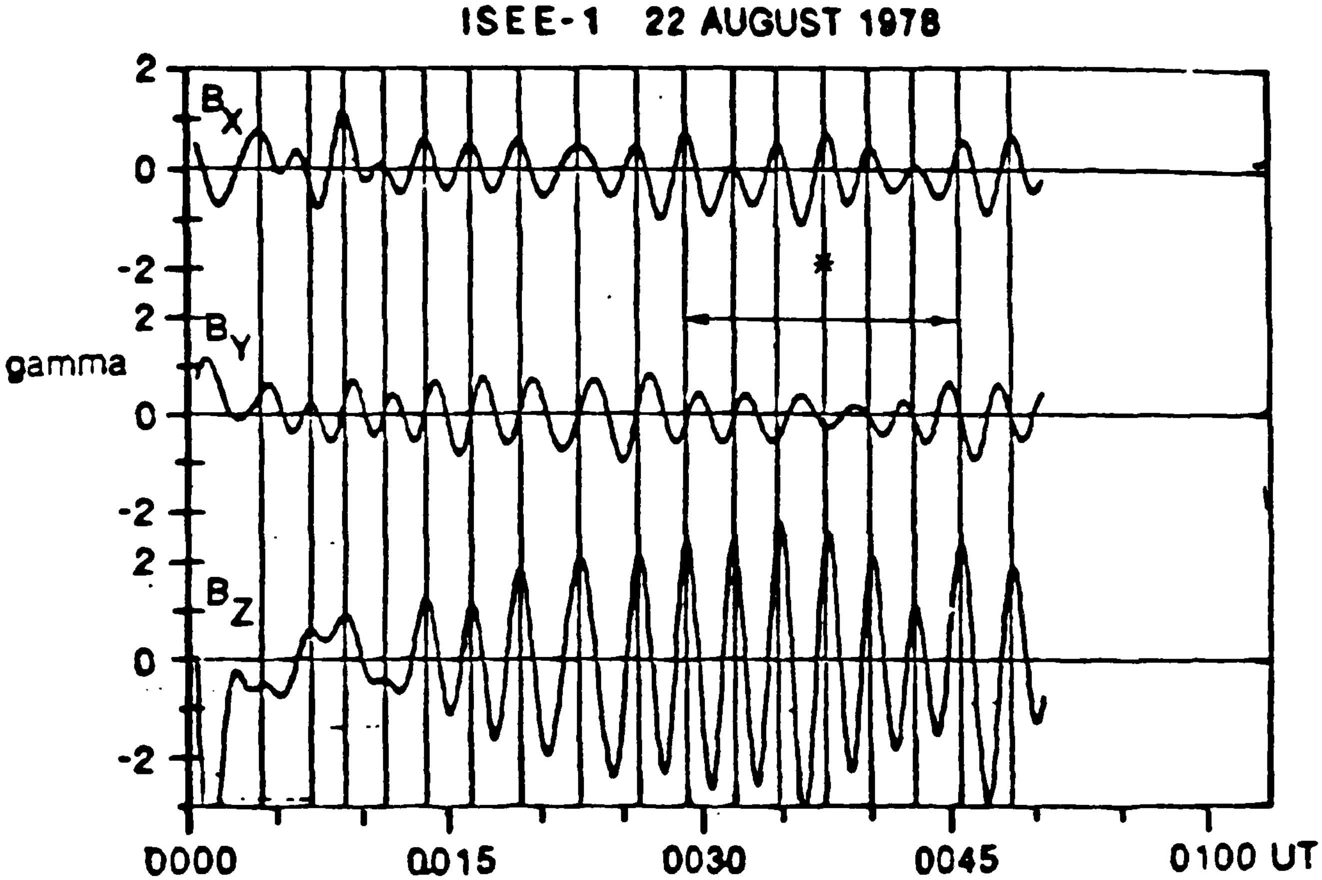

Figure 2. Phase reversal of B_y component of Pc5 in ISEE-1 record.

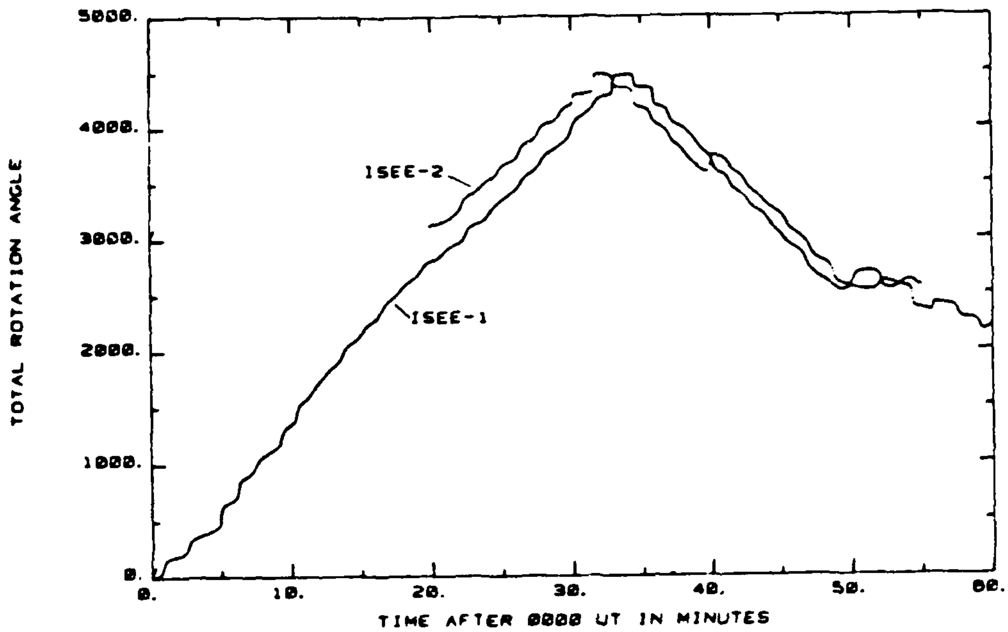

Figure 3. Cumulative rotation angle, i.e., phase, of transverse field components at ISEE 1, 2 relative to phase at 0000UT, 18 August 1978

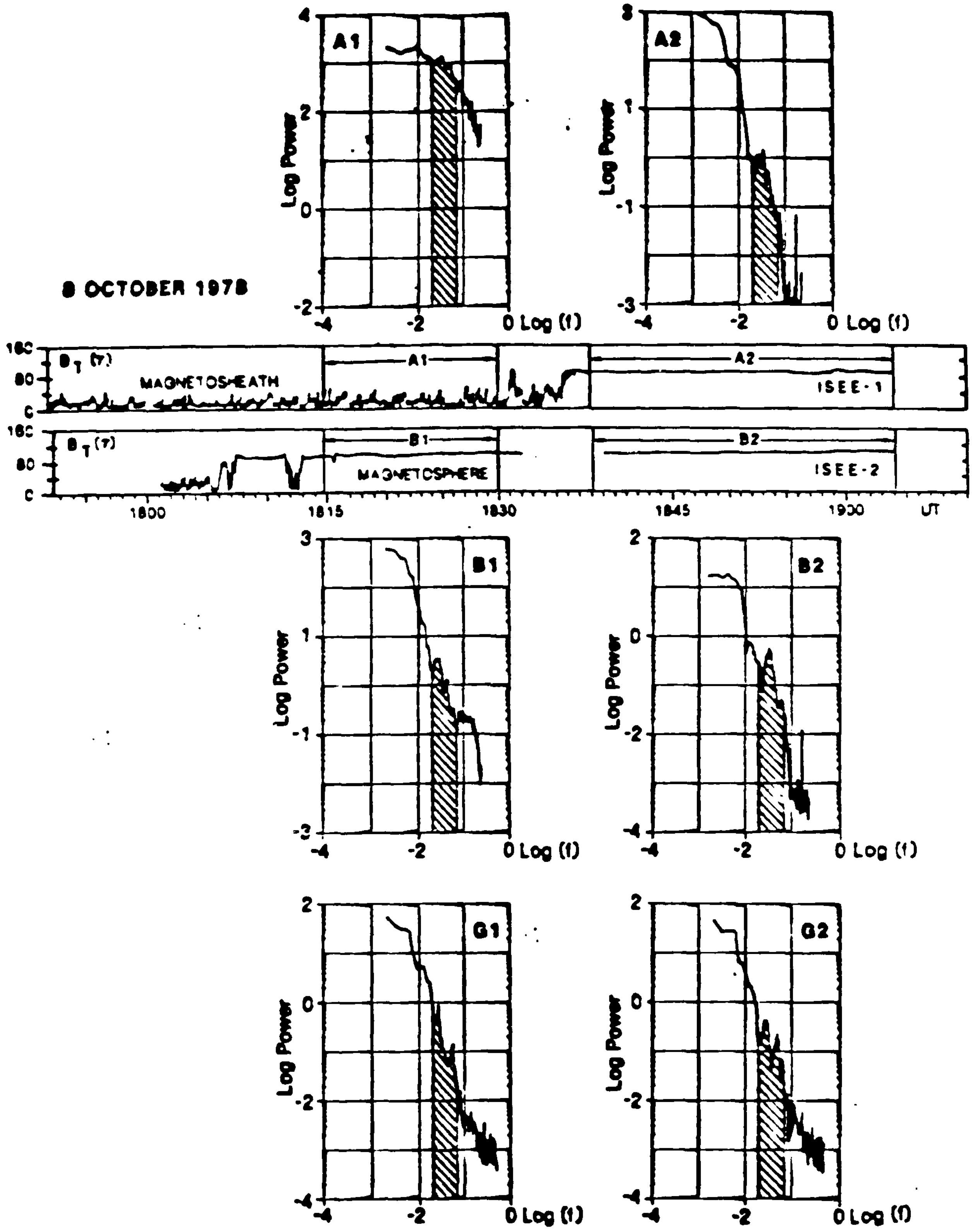

Figure 4. Spectra surounding a straddle inbound on 8 October 1978. "A", "B", and "G" signify ISEE-1, ISEE-2, and AFGL Newport, Washington, respectively.

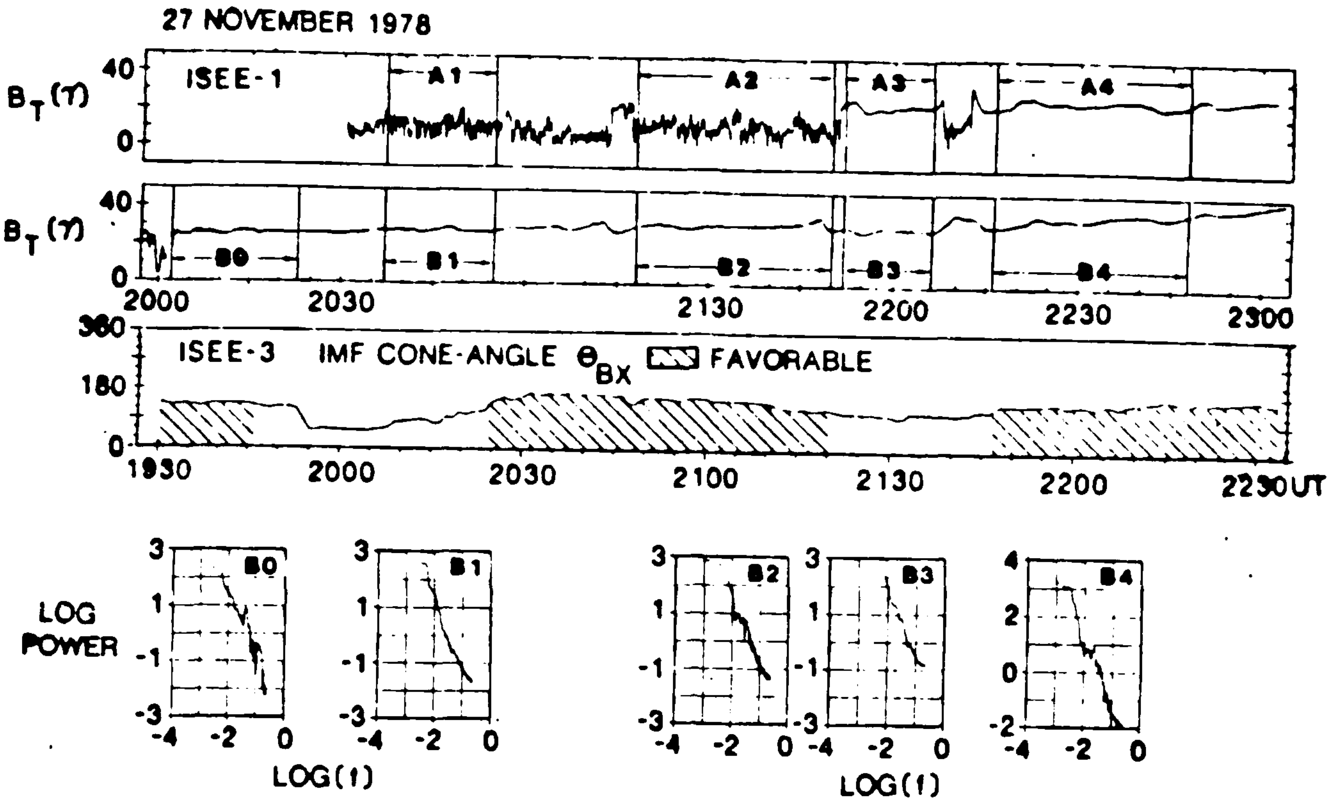

Figure 5. Comparison of ISEE-1, ISEE-2 data for straddle of 27 November; cone-angle between the IMF and the solar wind from ISEE-3 shifted 30 minutes to account for delay to vicinity of earth; and sequence of magnetospheric spectra at ISEE-2. Shading in the cone-angle panel denotes intervals during which the IMF orientation was favorable to quasi-parallel geometry at the subsolar bow shock.

APPENDICES

APPENDIX A

A STORM-TIME, PC5 EVENT OBSERVED IN THE OUTER MAGNETOSPHERE BY ISEE 1 AND 2: WAVE PROPERTIES

E. W. Greenstadt (Space Sciences Dept.,
TRW Space and Technology Group

Redondo Beach, California 90278

R. L. McPherron, M. Hoppe, R. R. Anderson, F. L. Scarf

Compressional Pc5 magnetic pulasations are often observed at the dusk meridian of synchronous orbit during magnetospheric substorms. An association with diamagnetic decreases in the main field suggests that the waves are caused by an instability of ring current protons. We are investigating this hypothesis using magnetic field observations from the spacecraft ISEE 1/2. Throughout an afternoon sector, inbound pass on August 21-22, 1978, compressional Pc5 pulsations were seen from the magnetopause to inside the plasmapause at about 7 Re. In the outer magnetosphere the waves were irregular with frequency of order 4mHz, but on the plasmapause they became extremely monochromatic with frequency 6mHz. Everywhere the wave power in the compressional component was a relatively constant fraction, 80% of the total power. The waves were polarized in a magnetic meridian plane with the major axis at nearly a constant angle of 20° to the main field.

In the outer magnetosphere wave ellipticity was of order 0.2 while on the plasmapause it varied systematically from right elliptical, through linear at the point of maximum power, to left elliptical. A cross correlation between the two spacecraft shows in phase variations in the outer magnetosphere and a 12 second delay at the plasmapause such that the leading spacecraft, closer to the earth and to midnight observed the waves first. Particle flux modulation was observed at the plasmapause with energetic protons in antiphase, and electrons in phase, with the compressional component. The association of a polarization reversal with a peak in the compressional component and particle flux modulation suggests a coupling between field line resonance and a drift or bounce resonant instability.

APPENDIX B

DRAFT REPORT

A STORM-TIME, Pc5 EVENT OBSERVED IN THE OUTER MAGNETOSPHERE BY ISEE 1 AND 2: WAVE PROPERTIES

E. W. Greenstadt (Space Sciences Dept., TRW Space and Technology Group, Redondo Beach, California 90278)

R. L. McPherron (Institute of Geophysics & Planetary Physics, University of California, Los Angeles, California 90024)

M. M. Mellott (Institute of Geophysics & Physics, University of California, Los Angeles, California 90024)

R. R. Anderson (Dept. of Physics & Astronomy, University of Iowa, Iowa City, Iowa 52242)

F. L. Scarf (Space Sciences Dept., TRW Space and Technology Group, Redondo Beach, California 90278)

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Bldg R-1, Rm 1176
TRW Space and Technology Group
One Space Park
Redondo Beach, California 90278

ABSTRACT

A STORM-TIME DUSK Pc5 EVENT OBSERVED IN THE OUTER MAGNETOSPHERE BY ISEE 1 AND 2: WAVE PROPERTIES

A classical, storm-time Pc5 event ($T \sim 170$ sec) was recorded by the satellite pair ISEE 1, 2 during an inbound, nearly equatorial pass in the dusk sector on 21-22 August 1978. Irregular and quasi-periodic pulsations, possibly composed of several harmonics ($f \sim 2\text{-}12 \times 10^{-3}$ Hz) were recorded from just inside the magnetopause at 11 R_E to a distance of 8 R_E where the pulsations became nearly sinusoidal and disappeared at 7 R_E just at the outside edge of the plasmapause. Comparison of signals from the two spacecraft throughout the pass shows remarkable similarity of waveform at the second spacecraft following a few hundred to a thousand kms ($\sim$300 sec) behind the first. This duplication of wave forms with periods commensurate with the spacecraft separation time suggests that the two satellites were sampling slightly different phases of the same wave cycle. The more distant, irregular pulsations were encountered by the two spacecraft with essentialy no consistent delay between them, while the innermost, regular waves were always encountered first by the leading spacecraft. Cycle-by-cycle hodograms show nearly linear or highly elliptical polarization close to the meridian plane everywhere on the inbound orbit. During the last few cycles the ellipses broadened and reversed phase just before the oscillations terminated. The Pc5 pulsations occured during an interval of strongly southward interplanetary magnetic field and substorm activity and were accompanied by Pc1 waves at the spacecraft.

INTRODUCTION

Waves classified morphologically as Pc5 in the records of geomagnetic observatories on the earth's surface have also been recorded in the magnetosphere by satellites. These waves occur at geosynchronous distances (Barfield & McPherron, 1979) and have been recently classified into morning and dusk types by Kremser et al (1981). The waves in the dusk meridian are associated with substorms and with the plasmapause (Lanzerotti et al., 1974) which is where geosynchronous orbiters are most likely to see them (Barfield et al., 1972). There has been little opportunity to examine the storm-connected waves in the dusk meridian outside of L ~ 6 because eccentric satellites pass so rapidly through their region of occurrence, and do so only during certain seasons. Indeed, only a few examples of these pulsations outside synchronous orbit were displayed by Hedgecock (1976) despite inspection of data from many orbits of HEOS.

A fresh opportunity to observe these evening sector pulsations was provided by the satellite-pair ISEE-1, 2, launched in October 1977. During the first season of passes through the dusk sector, in August 1978, an outstanding event was detected by several plasma and energetic particle experiments as well as by the magnetometers. We anticipate that a full characterization and improved understanding of storm time Pc5 pulsations in the dusk sector, will eventually emerge from the treasury of data collected. In this initial report, we describe the event, and its geomagnetic context as recorded by the magnetometers and plasma wave detectors, develop evidence of close association between waves in the outer magnetosphere and monochromatic waves at the plasmapause, characterize the radial polarization of the monochromatic transverse components as the profile of a resonant region, and directly measure the radial thickness and detect the probable motion of the resonance shell. We use one of the unique advantages of the ISEE system namely, the simultaneous observations by two spacecraft close together in the same eccentric trajectory and a third spacecraft upstream monitoring the solar wind. This advantage has already proved its value in studies of pulsations of the morning magnetosphere (Singer et al., 1979).

THE EVENT IN CONTEX

Spatial context. The magnetic wave signature for the inbound magnetospheric pass of 21-22 August 1978 is displayed in Figure 1. The three components of the ambient field measured by ISEE-1 are plotted in GSM coordinates (X toward the sun, the X-Z plane containing the dipole axis), together with the total field magnitudes B from both ISEE-1 and ISEE-2. The similarity of waveform, cycle by cycle, at the locations of the two spacecraft is visible throughout the pass. To place the wave in context of the ISEE magnetospheric profile, we have included an insert of the 64-second average of B_T at ISEE-1 in the upper left, where the shaded section corresponds to the interval displayed in the larger figure. The waves first appeared shortly after the spacecraft crossed the magnetopause and continued essentially to the plasmapause, as we shall show later. The similarity of the wave observations to cases described by Hedgecock (1976) can be appreciated by comparison with his figures 3 and 4. The event on which we concentrate in this report is the sequence of regular waves that began as early as 2345 UT, certainly no later than 0015, and ended at 0050. In the insert, the darker shading denotes this event. The dark, high frequency noise superimposed on the Pc5 pulsations from about 0030 is caused by Pc1 pulsations which continued deep into the magnetosphere.

The spatial region over which the wave event was observed is shown in several coordinate planes in the various panels of Figure 2. In each of the orbit panels the magnetospheric waves are denoted by an elongated box enclosing the trajectory; the Pc5 event occurred where the inner end of each box is shaded. The asterisks on an arc of geosynchronous trajectory in the drawing at lower left signify the locations of GOES-2 and GOES-3 at the time of the Pc5 event.

We see that the data were obtained near the magnetic equator, just sunward of the dusk meridian, from slightly inside the magnetopause to slightly outside the radius of geosynchronous orbit. In fact, the Pc5 event occurred outside the synchronous elevation. This is significant because, with the exception of Hedgecock's (1976) observation virtually all Pc5 wave activity measured in the magnetosphere has been detected with geosynchronous satellites or STARE arrays and attributed to processes associated with the plasmapause. The 22 August event must then signify either an expanded plasmapause, a detached plasmapause like boundary, or a source mechanism unrelated to the plasmapause.

The separation vector of the two satellities during the Pc5 event is shown in the panel at the top of Figure 2. ISEE-2 was leading ISEE-1 inbound and southbound, almost in a common meridian plane, by 960 km. The Z separation, not shown, was about 200 Km, with ISEE-1 closer to the equator than ISEE-2. The radial distance of ISEE-2 to Earth is of course, not drawn to the same scale as the separation distance in this panel.

The actual relationship of the magnetic waves to the plasmapause in the present case can be obtained from Figure 3, where B at ISEE-1 is plotted over a wideband spectrogram of the simultaneous electric wave data, also from ISEE-1. Electron density is related to the observed plasma frequency by $n(cm^{-3}) \simeq f^2/80$, f in KHz. The sinusoidal Pc5 waves occurred at the beginning of the gradient in electron density associated with the plasmapause.

Temporal context. The interplanetary magnetic field at ISEE-3 turned almost directly southward in GSM coordinates at 2025, about an hour and a half before ISEE-1 and 2 entered the magnetosphere and encountered the waves we describe. The discontinuity reached the two spacecraft at 2108, some 43 minutes after it passed ISEE-3, almost simultaneously with the magnetopause crossing by the satellite pair. The upper panel of Figure 4 shows the IMF record at ISEE-3. Following the initial interval of almost purely southward field for over an hour, the GSM X and Y components increased, but the negative B_Z continued to dominate, and for the next three hours the solar wind provided an outstanding example of sustained southward magnetic field. The magnetospheric substorm caused by the episode of southward IMF began just before 2200. The lower panel of Figure 4 shows that the bulk of the substorm as defined by two surface stations, coincided with the pass of ISEE-1, 2 though the outer magnetosphere, signified by the shaded strip, which ended with the Pc5 event near the plasmapause.

WAVE ANALYSIS

Frequency spectra. Spectra were calculated by first editing, detrending and fast-Fourier-transforming the magnetic field vector time series. The Fourier transforms of each component were then multiplied to obtain auto and cross spectra at each Fourier coefficient. These Fourier spectra were low pass filtered with a running average, normalized, and plotted. The frequency resolution of the resulting spectra, defined as the distance between totally independent estimates is given by

$$\Delta f = NB/(2*Nest*\Delta t)$$

where NB = number of points in filter

Nest = number of Fourier coefficients (half number of data points)

Δt = time resolution of data (4.0 seconds)

Spectra calculated for half hour intervals, filtered with a 3 point running average have a resolution of 1.7 mHz. The actual location of the frequency of peak power can be determined somewhat more accurately than the resolution as every filtered Fourier spectral estimate is plotted.

Figure 5 displays three sets of power spectra corresponding to selected segments of ISEE-1's field data. Each spectral panel represents the frequency analysis of the time series above it, to which it is referenced by the slanted lines. The first two segments are spaced through sections of the outer magnetosphere, the last covers the heart of the pulsation event itself.

Spectral power was distributed differently with frequency along different parts of the trajectory, but all spectra share two common characteristics: Each has at least one clear peak, plus other lesser ones; and one component of the field carries most, if not all, of the power in every peak, indeed, throughout every spectrum. The second characteristic implies the waves were essentially linearly or highly elliptically polarized everywhere at all frequencies. Examination of the 3-point spectra discloses two dominant peaks with maxima at frequencies, 4.0 and 6.0 mHz. The lower frequency was present immediately inside the magnetopause and persisted until about 2320 at a distance of 9.3 R_E. The higher frequency signal appeared to be present throughout, but its amplitude was enlarged after 2320 and was mixed with still higher frequency signals of 9 and 12 mHz. After 0000 UT there was a change in the characteristics of the pulsations which became very monochromatic at a frequency close to 6.0 mHz. The ULF wave activity vanished suddenly about 0050. A zero crossing analysis of the waveform 0000-0050 interval gives periods around 167$\pm$2 seconds ($f = 5.99 \times 10^{-3}$ Hz), in agreement with the 167-second period determined from the spectral peak for this interval.

Four significant peaks have been emphasized and labeled in Figure 5; three of them at 85, 167, and 250 second periods, immediately suggest harmonic pairs of, roughly, 4 and 12×10^{-3} Hz, or 6 and 12×10^{-3} Hz. The fourth, at 110 seconds, suggests that the broad 250 second peak may include an element (T = 220 sec.) of another pair, 85 and 9×10^{-3} Hz. The harmonic number in any of these potential sequences appears to have increased with decreasing radial distance. Verification of such sequences, and their relationships to magnetospheric geometry, will require further study, probably outside the resolution of this data set.

Polarization. Cycle-by-cycle hodograms confirm an extremely elliptical polarization of through almost the entire duration of the wave event, as already indicated above by the power spectra. Four examples, each showing planes of maximal and minimal variance are shown in Figure 6, where the disturbance vectors are seen to have traced long, narrow, irregular patterns confined almost entirely to the planes of maximal variance.

To examine details of wave polarization during the inbound passage of the ISEE spacecraft, we performed a cycle-by-cycle minimum variance analysis. This analysis included several steps. First, the entire orbit was divided into intervals over which the direction of the magnetic field was approximately constant. For each interval a field-aligned coordinate transformation was defined using the direction of the average field for the Z axis; a direction perpendicular to the plane defined by the field and the spacecraft position vector as the Y axis; and the outward field normal defined by the cross product of Y and Z as the X axis.

Data in each interval were rotated from spacecraft to field-aligned coordinates and then bandpass filtered. The pass band, 2-8 mHz, was chosen to include the two predominant peaks at 4 and 6 mHz revealed by spectral analysis. Next, the pulsation waveform was examined visually and successive cycles of the pulsations were defined by an interactive graphics program. For each interval thus defined, minimum variance analysis was performed to obtain properties of the magnetic perturbation within the pass band of the filter. These properties included the total and component power in the perturbations, the apparent wave period, the orientation vectors of the perturbation ellipse, and the sense of rotation.

Results of the foregoing analysis are summarized in Figures 7 to 13, which show the temporal changes in wave properties as the spacecraft ISEE-1 moved inward. The plots begin at 2200 UT as ISEE-1 entered the magnetosphere and continue until 0100 when it entered the plasmasphere. Figure 7 shows the total power in the perturbation in the top panel, and the ellipticity in the bottom panel, where ellipticity is defined as the ratio of the minor to major axis of the perturbation ellipsoid. There were three intervals of large amplitude wave activity roughly centered at 2200, 2300 and 0030 UT (see Figure 1). In the first interval of intense, long period waves the ellipticity was small, indicating nearly linear polarization. During the second interval the ellipticity was somewhat higher, ~0.3. In the third interval, however, the period of the waves was shorter and the ellipticity varied systematically with amplitude. As the waves were first seen, the ellipticity was high, ~0.6. Then, as the spacecraft moved inward and wave amplitude increased, ellipticity decreased. At the point of maximum power in the parallel component the waves were linearly polarized. Subsequently, as wave power decreased the ellipticity again increased. However, the sense of rotation was reversed as a consequence of a 180° phase change in the azimuthal component. Outside the maximum in parallel power the transverse magnetic perturbation was right elliptically polarized, while inside it was left elliptically polarized. Figure 8 illustrates these points with filtered waveform plots and superimposed vertical lines of constant phase.

The upper panel of Figure 8 shows the three components at ISEE-1 in field aligned coordinates for the key 50 minutes of the third, monochromatic, interval. A maximum is clearly seen in the compressional component, with largest amplitude at around 0035. The verticle lines through the positive peaks of B_Z line up with the positive peaks of B_r, but we see the alignement is violated in comparing the B_o waveform. The detail in the linked panels below, from 0020 to 0040, shows that in comparison with the positive peaks of total field B_T, the azimuthal component shifted by 180°, from correspondence with the ascending zero-crossings to correspondence with the descending zero-crossings with the phase of B_T. This 180° change in phase was coincidental with the amplitude maximum of B_Z, and is the expected signature of the azimuthal component of a standing, resonant, transverse wave. The 180° phase shift occurred over five or six cycles of the wave; from the period of 167 seconds and the spacecraft velocity of 2.7 Km/sec., we infer a resonance-region radial thickness of 2250 to 2700 Km, or 0.35 to 0.42 R_E. This first direct measurement from a complete radial pass through a magnetospheric resonance agrees well with previous thichness estimates from less continuous data (Hughes et al. 1978; Hughes, 1980).

A cumulative area analysis has also been applied to the filtered and transformed data. In this analysis it is assumed that the tip of the magnetic perturbation vector projected in a coordinate plane, no matter how erratic its progress, rotates around a series of ellipses as a function of time. As the vector rotates, the angle of rotation and the area swept out by the vector change depending on the properties of the wave. If the perturbation is linearly polarized neither changes. If it is right-hand elliptically polarized (counterclockwise in the X-Y plane) both increase with time. A change in the sense of rotation causes an extremum in both parameters.

Application of the cumulative area technique to data from ISEE-1 gives the results summarized in Figure 9. The three traces show the cumulative area, cumulative rotation angle, and the instantaneous wave power (amplitude squared) as functions of time for the first hour of 22 August. The amplitude resonance associated with the phase reversal of B , although not obvious in either transverse component alone, appears, as expected, in their combined magnetic perturbation vector, i.e. in the wave power perpendicular to B, $b_\perp = b_r + b_\ddagger$, plotted as the dotted curve in the figure. Twice each cycle of the perturbation this vector passes through maxima and minima corresponding to times of alignment with the principal axes of the ellipse. If the perturbation is linearly polarized the vector varies between zero and some positive value. If it is elliptically polarized it varies between two positive values whose ratio is the instantaneous ellipticity of the perturbation. In Fig. 9, the oscillating, transverse wave magnitude is seen to have reached a sharp peak between 0030 and 0040 exactly when the cumulative area and angle swept out by the rotating b (solid curves) reached their maxima, indicating that the transverse power maximized when the sense of polarization reversed and each cycle's polarization parameters began to be subtracted from the cumulative totals. Note that the slope of the rotation angle trace gives the instantaneous wave period. Approximating the average slopes by straight line segments yields an initial wave period of 150 sec., followed by an interval of wave period about 180 sec., and a post-reversal period of about 190 sec. The average of these periods, weighted by the lengths of the intervals used to evaluate each slope, is 170 sec., close to the 167 sec. peak of the spectrum computed over the whole interval.

It is evident from the angle and rotation traces that at the beginning of the interval the perturbation was right-elliptically polarized (positive slope). As time progressed, the polarization became more and more elliptical until at 0034 UT it was exactly linear. Subsequently the polarization continued to change, becoming left-handed throughout the remainder of the interval.

Resonance offset. A similar analysis of ISEE-2 data produced the results plotted in Figure 10, but with a time-offset accounted for by this spacecraft's earlier arrival in the resonance shell. There was also an offset of the maximal amplitude at ISEE-2 from the maximal cumulative angle seen by the same magnetometer. However, since two of the b-max excursions (semi-major axes of $b_\perp$) correspond to each wave period, and the two spacecraft crossed the resonance about half a period apart, the absolute magnitude recorded at either satellite was highly sensitive to the wave phase at which the satellite chanced to arrive: ISEE-2 probably missed the actual conjunction of the two maxima.

The polarization reversal was observed earlier at ISEE-2 than at ISEE-1. Figure 11 exposes this point by superposing the area and angle traces from the two spacecraft. Both panels indicate that ISEE-2 encountered the polarization changes about three minutes (180 sec.) earlier than ISEE-1. As mentioned before (Fig. 2), ISEE-2 led ISEE-1 on the trajectory and passed through spatially localized features first. At the time of this event (~0037) the spacecraft were seperated radially by 880 km. The delay should have been ~325 sec. at a satellite velocity of 2.7 km/sec.

It thus appears that ISEE-1 encountered the polarization reversal earlier, i.e. further out, than it should have if the resonance shell were localized and stationary. One explanaton of this discrepancy is that the resonance region was moving radially. Of course if this explanation is valid, then the estimated thickness of the resonance reversal from either satellite would be too small, so 0.4 Re would have to be regarded as a minimal thickness, and double this value would not be unreasonable.

<u>Wave offset</u>. Returning to the lower panels of Figure 8, filtered waveforms from both ISEE-1 and ISEE-2 are plotted, which illustrate the character of the instantaneous offset, that is, the delay between the two records of the waves. The offset was virtually constant at an observed value of about 12 seconds between the two signal records. The offset is clearly visible in the B_T plot but is lost temporarily from B_O during the latter's phase shift, when the ISEE-2 signal actually vanished for one cycle. Physically, this offset means that ISEE-1, following ISEE-2 inbound, recorded each cycle of the wavetrain .072 period, or 26^o phase behind ISEE-2, where we have taken the average wave period as 167 seconds.

Radial invariance. The overall history of the time offset in the two signals is displayed in the bottom right panel of figure 12. Quantity Δt denotes the delay between detection of the same wave phase at ISEE-2 and ISEE-1, as drawn in the panel at bottom left of Figure 12. We note there was esentially no measurable delay in phase between the records of the two magnetometers in the outer magnetosphere until about 2330, when Δt attained values of 8 to 16 sec., which continued until the end of the interval. We will discuss this property again later.

The sketch at upper left defines angles θ and $\emptyset$ which characterized the polarization ellipse in the magnetic meridian plane. The three panels indicate clearly the relatively constant polarization of the waves thoughout the inbound pass: The perturbation ellipse was almost in the meridian plane before 2230 and after 2330 ($\emptyset \sim o$, 180°) and the major perturbation was close to the nominal B everywhere ($\theta \sim 10$ to 20°). The switch of $\emptyset$ between 180° and 0° at about 0005 is an artifact of the polarization code convention and has no physical significance. In general, deviations from the common values of θ, $\emptyset$ just described occurred when the filtered wave power was low (Figure 7); that is, when wave activity was minimal; so the common values truly represent almost fixed wave polarization during the three hours depicted. The major exception was the 0 orientation of about 240° during irregular waves between 2250 and 2330.

The plots of figure 12 illustrate one of the striking characteristics of the events of the 21-22 August pass; namely the tendency for most wave parameters to remain nearly constant in the data regardless of the location of the spacecraft. The angle $\emptyset$, for example, took little notice of the change in phase delay at 2330, and angle θ was substantially the same at the beginning of the interval as it was during the last hour and a half.

These characteristics are also apparent in Figure 13, where the cycle-by-cycle phase delay is reproduced in the first (top) panel for comparison with other parameters. The second panel presents the cycle-by-cycle period of each measurable wave cycle within the passband of the 2-8 mHz filter. Two horizontal dashed lines corresponding to the two predominant peaks in the power spectra are drawn at periods of 250 and 167 seconds. We see that the instantaneous periods at 100, 160 and 250 seconds tended to recur while the ellipticity in the third panel, replotted from Figure 7, was effectively stable between 0.1 and 0.3. when significant power was present, until ~0000 UT. The bottom panel shows even more emphatically that the compressional wave power $P_{||}$ was a substantial fraction of total power ($P_{||}/P_T$ 0.8) almost everywhere, independent of the interspacecraft phase delay (top panel) or the period (second panel). Thus throughout most of the inbound orbit and particularly during the intervals of high activity, roughly 80% of the power in the wave perturbation was parallel to the ambient field. Conversely, transverse power $P_{\perp}$ was typically less than 20% of the total power. We see further that the low ellipticity was independent of the wave period dominant at way particular time.

The foregoing observations argue that the wave phenomena encountered by the two spacecraft shared common properties essentially independent of radial distance within the narrow meridianal sector sampled in this case.

Surface observations. Magnetograms covering the interval of ISEE's inbound pass have been collected from the Air Force network, whose Rapid City, South Dakota (RPC), and Camp Douglas, Wisconsin (CDS), stations were at almost the same local times as the ISEE pass. Waves of irregular waveform and long period were recorded at all stations, but were most prominent between 2330 and 0100 UT at the RPC, CDS, and MCL (Mt. Clemens, Michigan) locations and appreciably reduced at Lompoc, Sudbury, and Tampa both west and east of ISEE's meridian. Identification of these waves as being the same as those found in the outer magnetosphere will require detailed spectral, polarization, and propagation analysis of digital data from these stations. Specifically, periods of 140-160 sec. appear to have been present.

Geosynchronous observations. As described in the lower panel of Figure 2, the GOES-2 and 3 satellites bracketed the local meridians of ISEE's trajectory. Each spacecraft recorded sharply defined bursts of pulsations, but at periods of roughly 60-80 sec, quite different from those seen by ISEE, with two exceptions: GOES-2 detected some radially polarized waves of 215 seconds period, and longer, between 0000 and 0300 UT, and GOES-3 detected some 162 sec compressional waves for over an hour, between 0210 and 0340 UT, as it passed through the meridians where ISEE had been before it entered the plasmapause. Here again, computer analysis will be required to decide whether the same phenomenon seen at ISEE was in progress as GOES passed the dusk meridian. For the present, two circumstances are clear: No observation point two hours or more away from the local time of ISEE recorded waves obviously similar to those at ISEE, and the waves apparent at geosynchronous elevation around 0300 UT had not been present shortly after 0100 when ISEE passed the radial distance of synchronous orbit. We thus conclude that the Pc5 pulsations were spatially located, confined to about 30° of longitude centered on, or an hour west of, the dusk meridian.

SUMMARY

Our initial investigation of the storm-time, dusk pulsation event observed by ISEE-1 and ISEE-2 on 21-22 August 1978, has disclosed the following properties of the waves composing the event:

1. Monochromaticity ($T \sim 167$ sec) in strong field and density gradient at the edge of the plasmasphere;

2. Dominant compressional component;

3. Well defined, classical resonance of the component transverse to B, with radial thickness of about .5 R_E;

4. Essentially constant phase difference $\sim 26°$ between spacecraft measurements of monochromatic waveforms surrounding resonance;

5. Irregular waveforms between the magnetopause and plasmapause, with spectra suggesting components harmonically related to each other and to the monochromatic segment;

6. Confinement to distant magnetosphere (outside plasmasphere) and limitation in longitude;

7. Resonance offset between spacecraft measurements incompatible with static resonance location.

8. Common parameters of phase, direction, and power throughout the data interval.

CONCLUSION

This phase of our investigation has expanded our concept of the region of the magnetosphere involved in the phenomenology of a resonant pulsation at or near the plasmapause. The radial dimension of our observations was some 4 R_E, greater than the roughly 3.4 R_E arc of the 30° sector in which our event seemed to be confined. The magnetic perturbations observed during the radial traversal of the dusk magnetosphere described in this report formed a complex wave event consisting of both compressional and transverse waves. These waves were coupled to each other, and wave activity in the outer magnetosphere appeared to be related to monochromatic waves associated with the anomalously distant plasmapause encountered at 7 to 8 R_E.

A classical transverse resonance signature was found within the monochromatic segment, but interspacecraft comparison suggests the resonance was moving outward, possibly because the plasmasphere was itself expanding. Overall evidence of coincident compressional and transverse maxima points to connection of the resonance with more distant wave activity, rather than to a manifestation of a purely local instability. Thus studies of pulsation resonances recorded by geosynchronous satellites are necessarily incomplete without a concurrent picture of the outer magnetosphere.

We expect future combination of the magnetometer data with electric field and charged particle measurements will determine the direction of propagation of the various wave components and delineate the most probable wave source or sources.

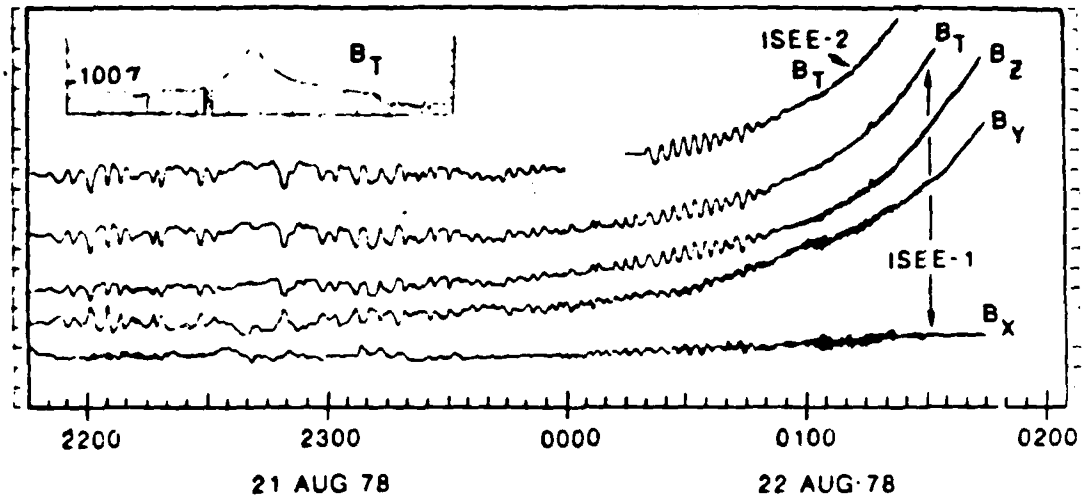


FIGURE 1. Time history of pulsations recorded by ISEE 1 and 2 during the inbound pass of 21-22 August 1978. Relation to geomagnetic field gradients shown as shaded section of insert.

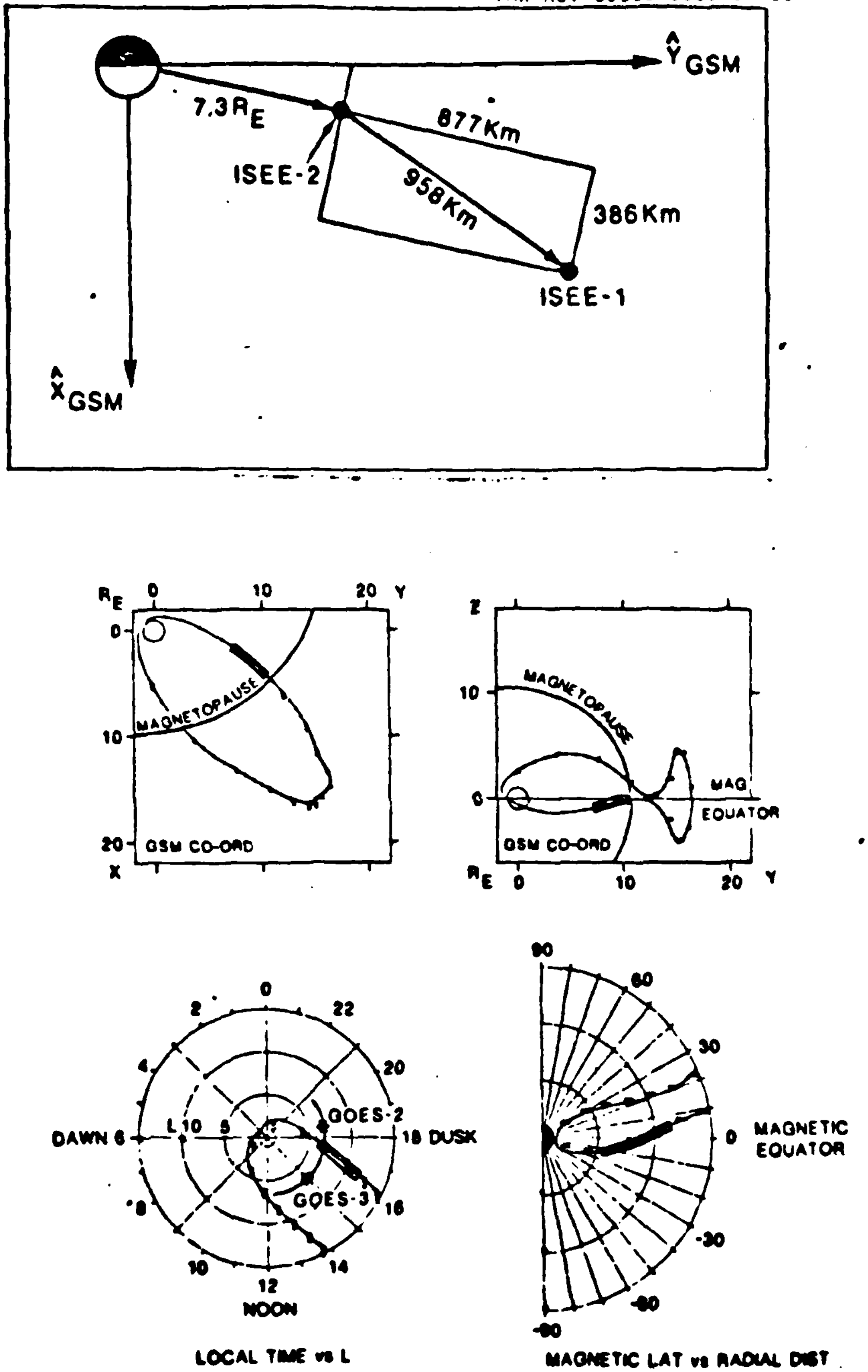
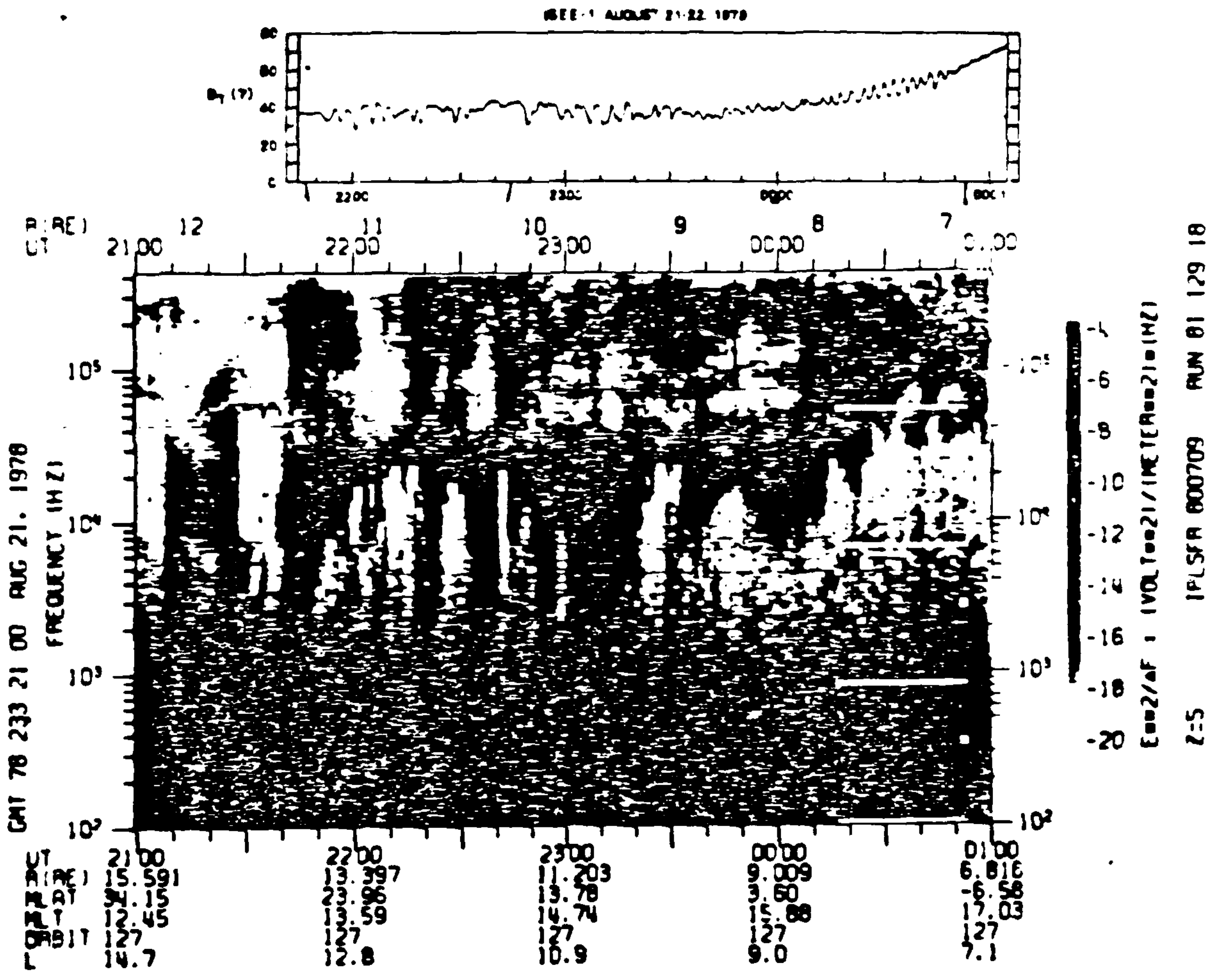


FIGURE 2. Lower four panels: Orbital geometry of the pulsation observations. Upper panel: orientation of the two spacecraft during Pc5 event of 0030 in Fig. 1. ..


ISEE-1 AUGUST 21-22 1978
FREQUENCY (HZ)
GMT 78 233 21 00 AUG 21, 1978
R(RE)
UT
ORBIT
IPLSFA 800709 RUN 81 129 18
Z:5

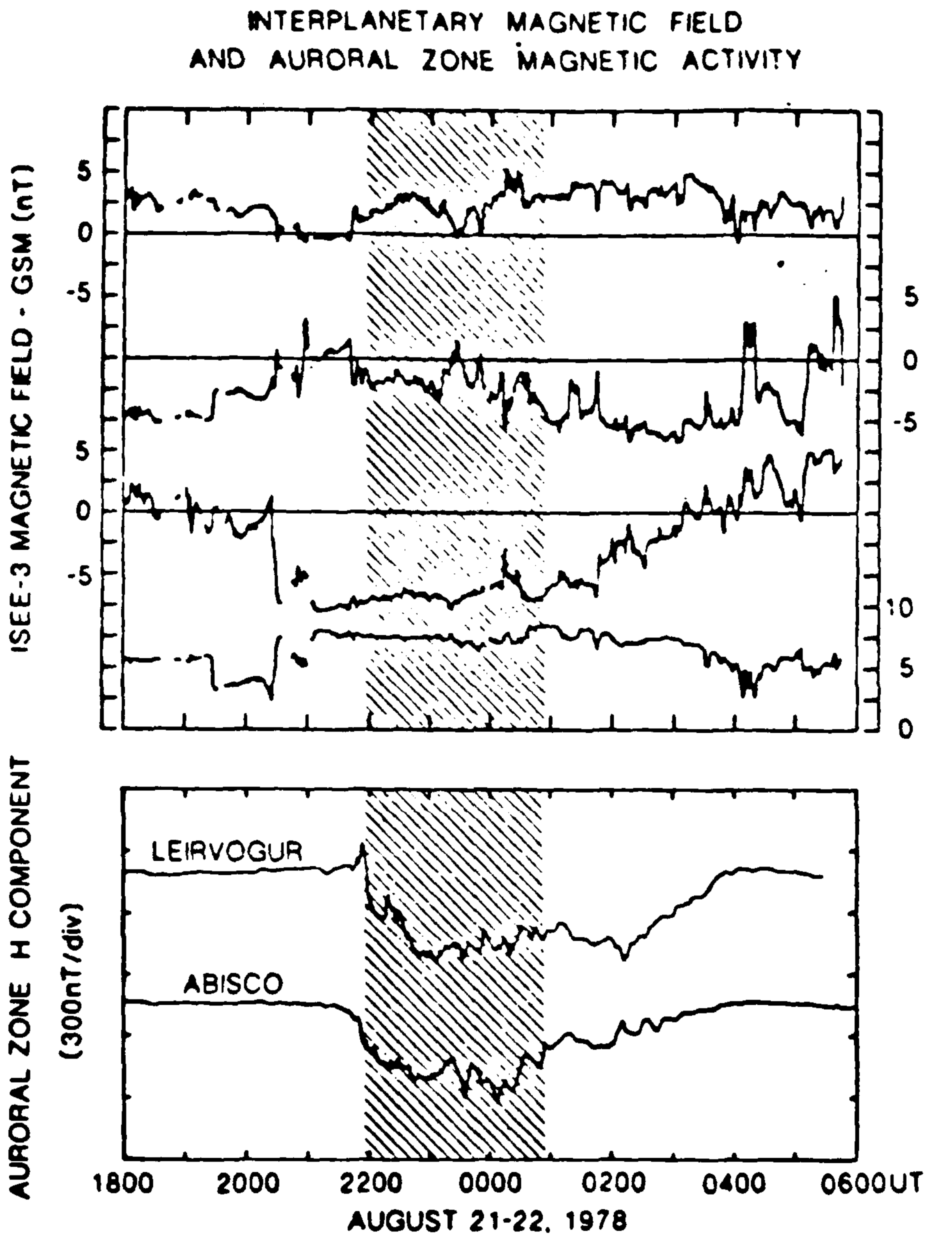
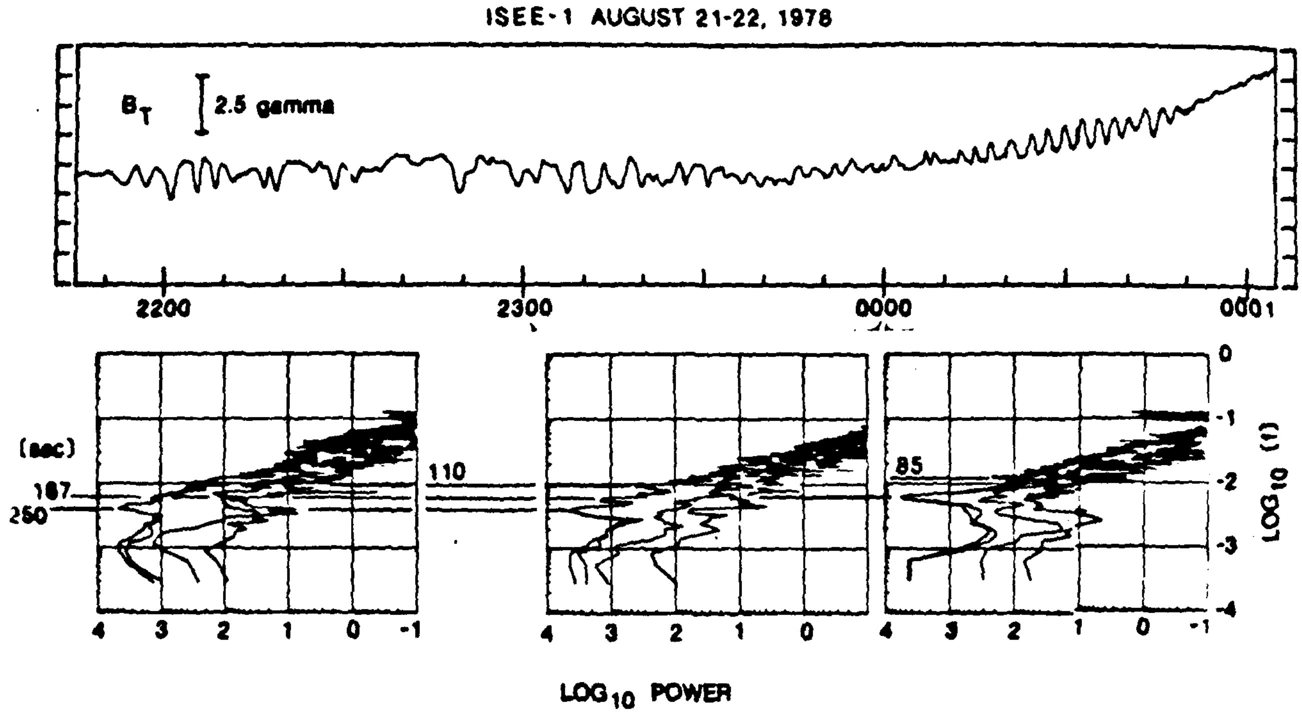


FIGURE 4. Upper; interplanetary field history surrounding pulsation pass (shaded) showing southward B_Z (third curve from top). Lower panel: two corresponding magnetograms showing substorm coincident with pulsation pass.


ISEE-1 AUGUST 21-22, 1978
B_T
2.5 gamma
2200
2300
0000
0001
(sec)
187
250
110
85
LOG_{10} (f)
LOG_{10} POWER

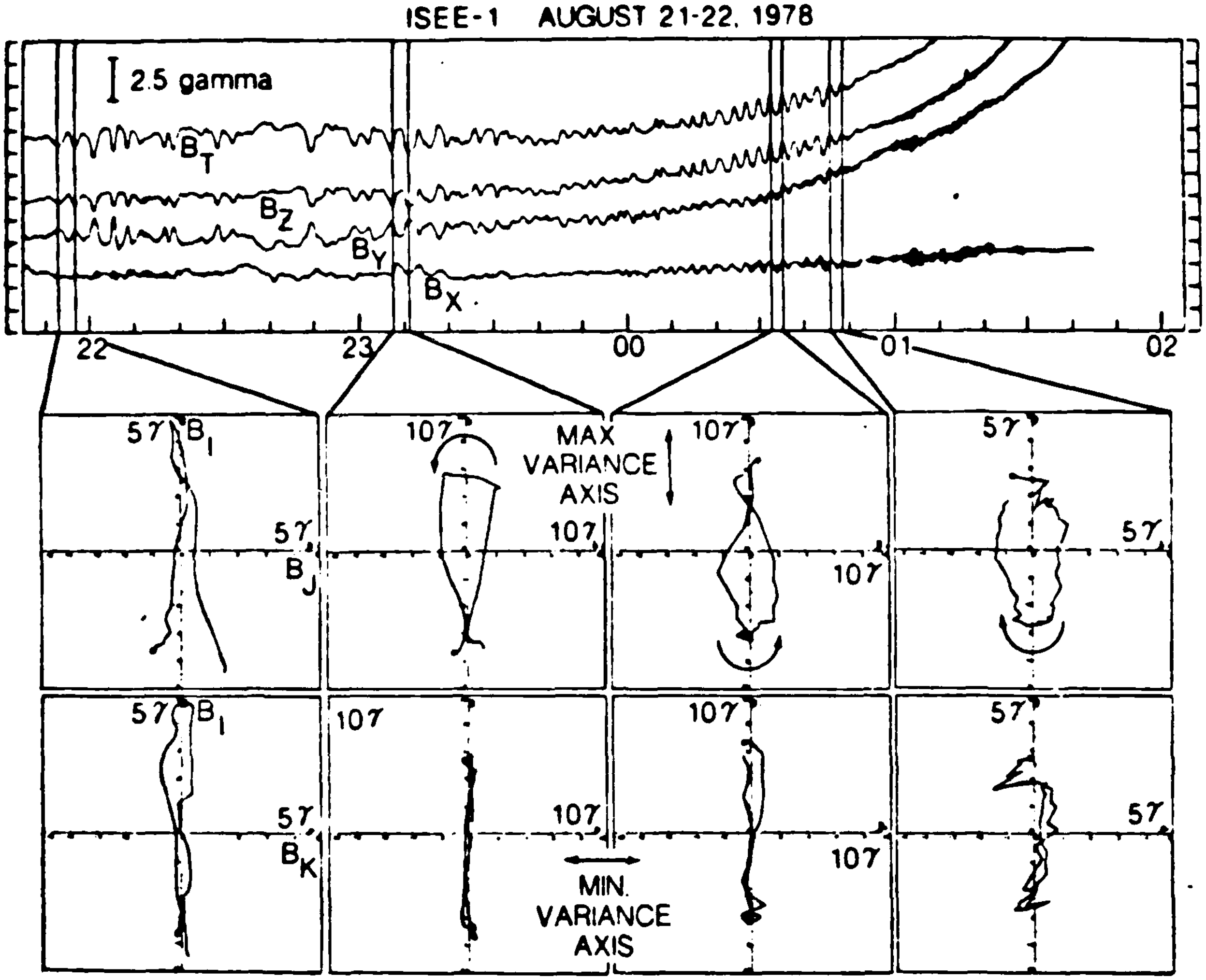
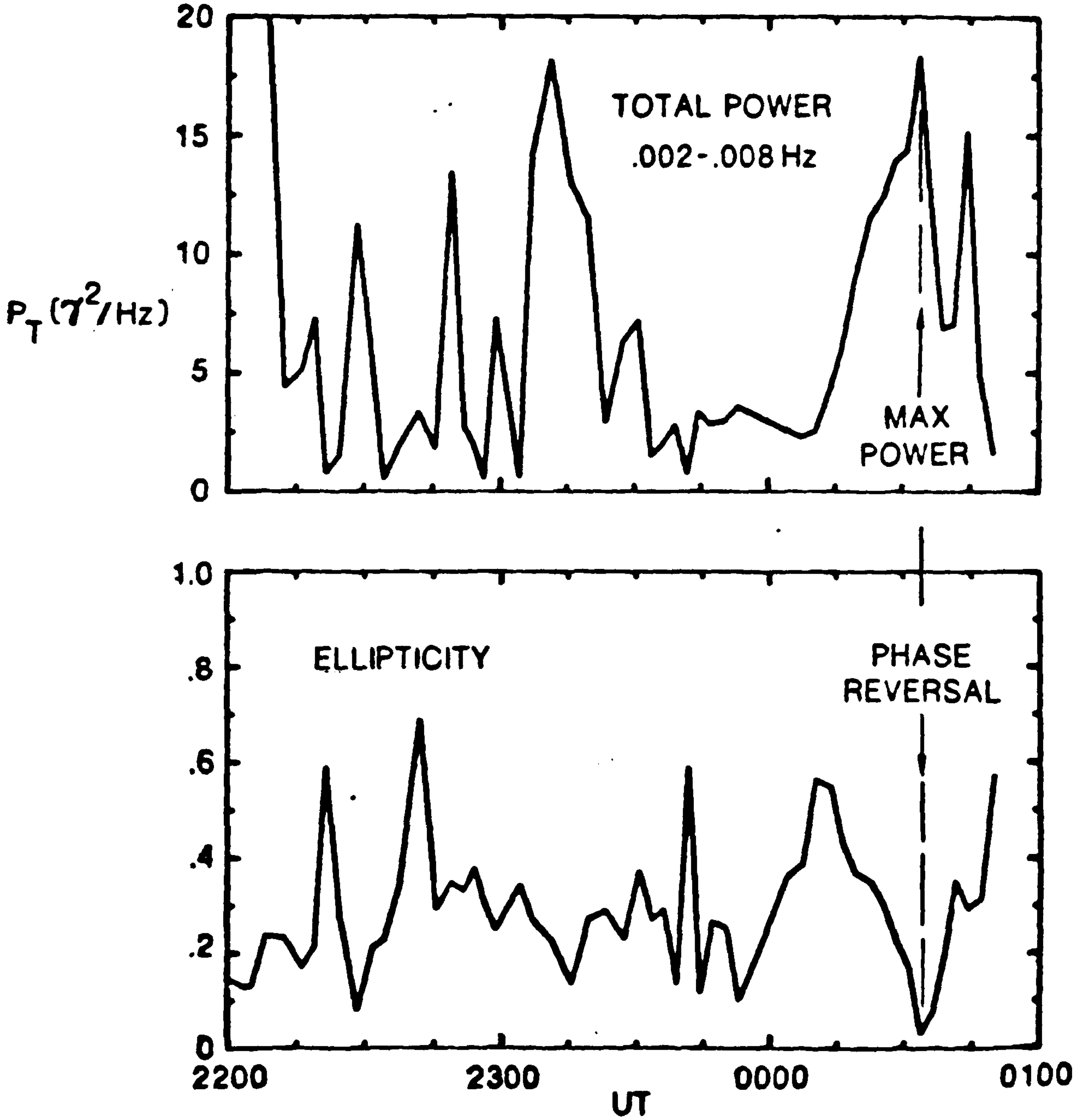


FIGURE 6. Polarization hodograms typical of individual pulsation cycles.


20
15
10
5
0
$P_T (\gamma^2/Hz)$
TOTAL POWER
.002-.008 Hz
MAX
POWER
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.8
.6
.4
.2
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ELLIPTICITY
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2200
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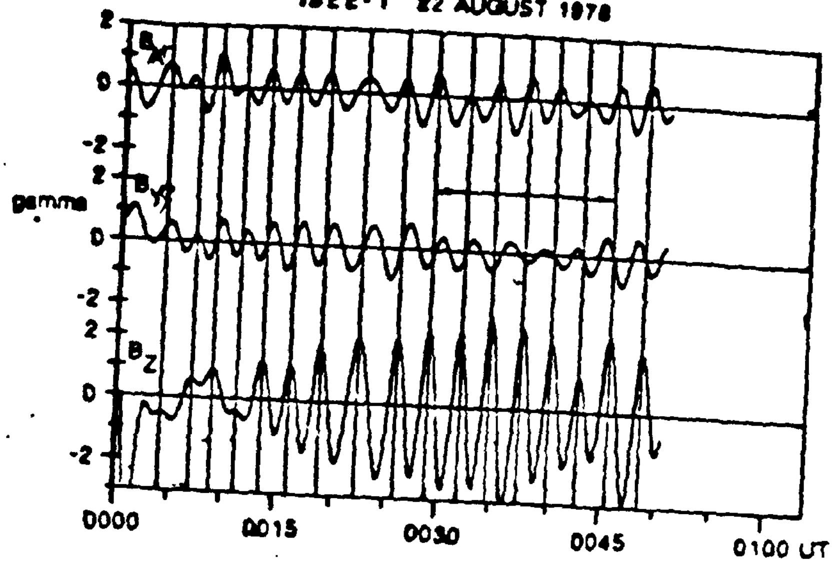
ISEE-1 22 AUGUST 1978
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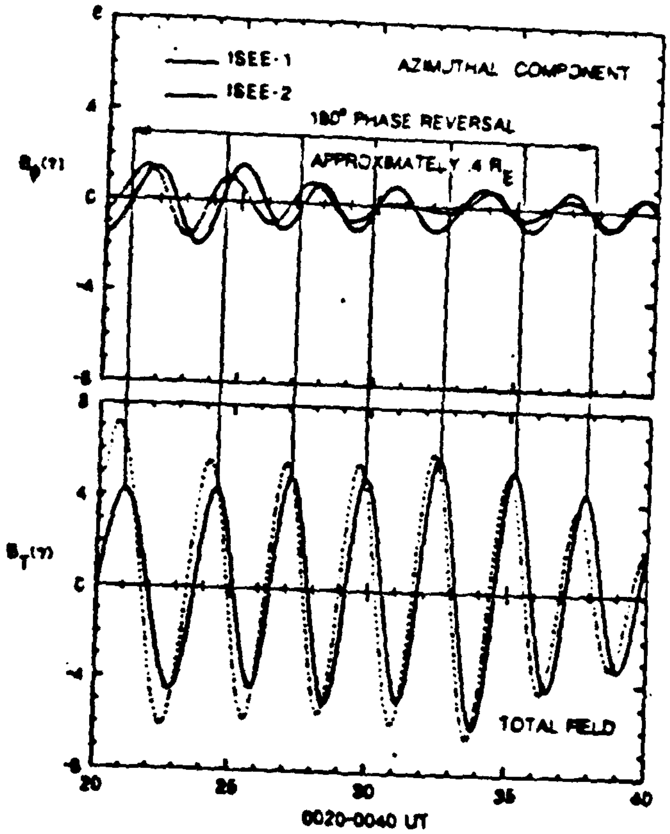
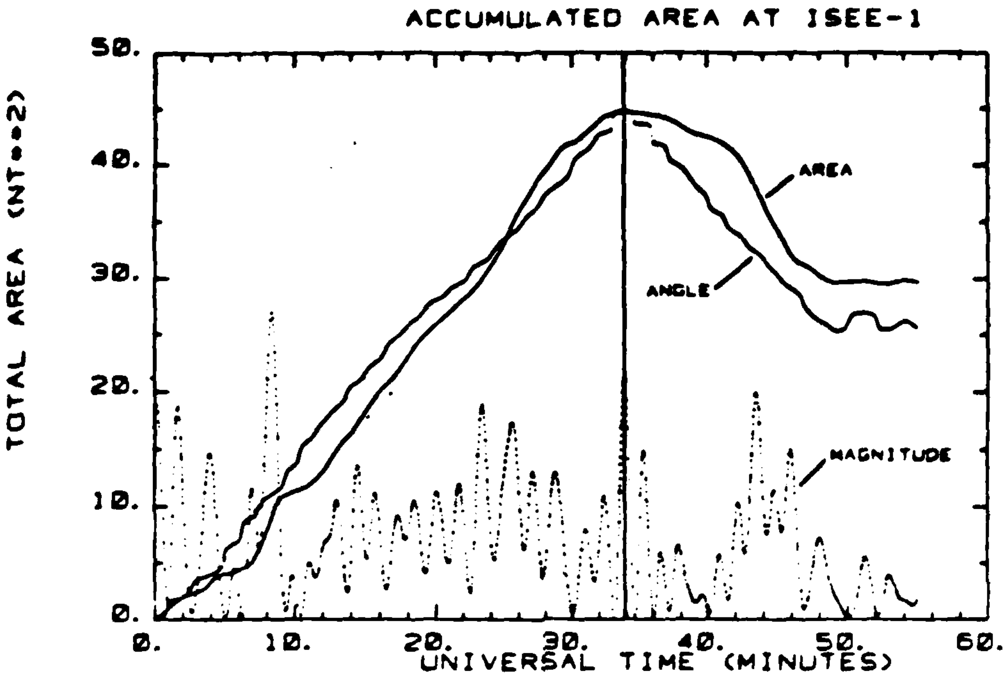
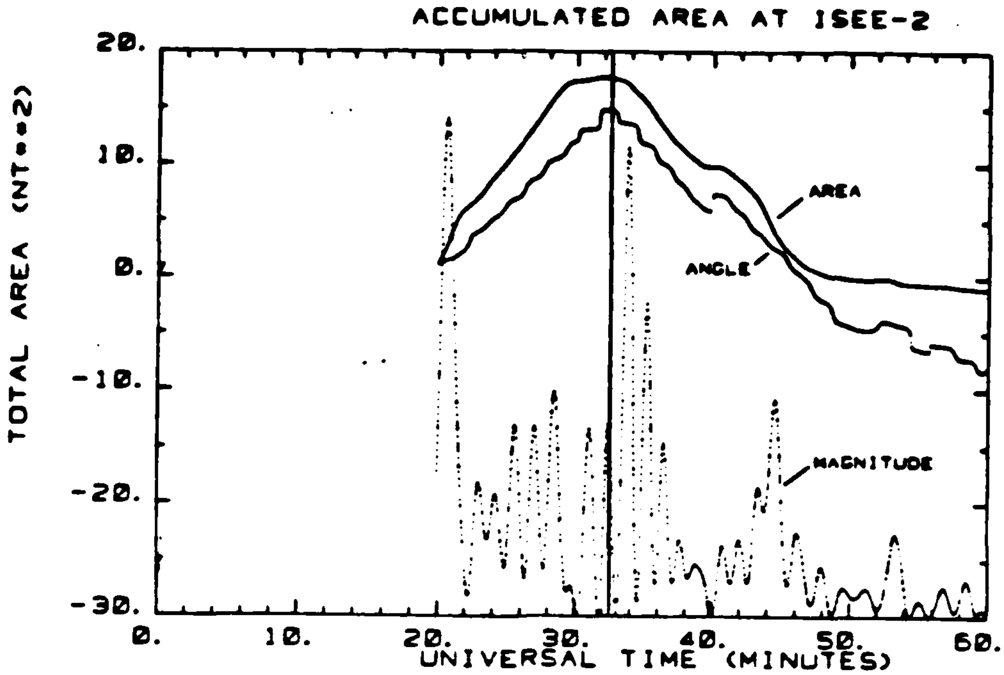
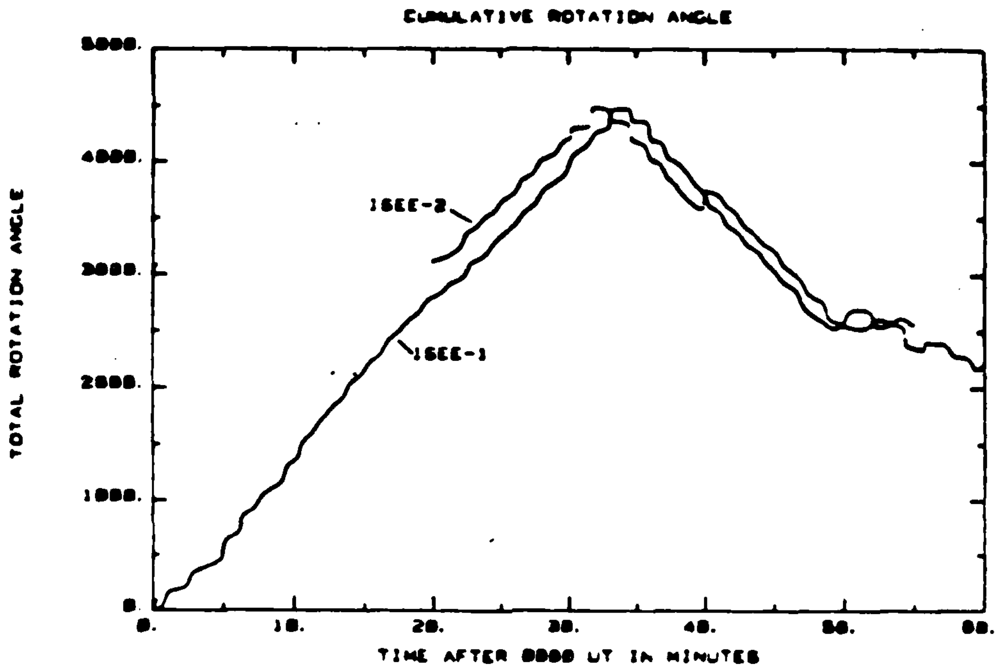
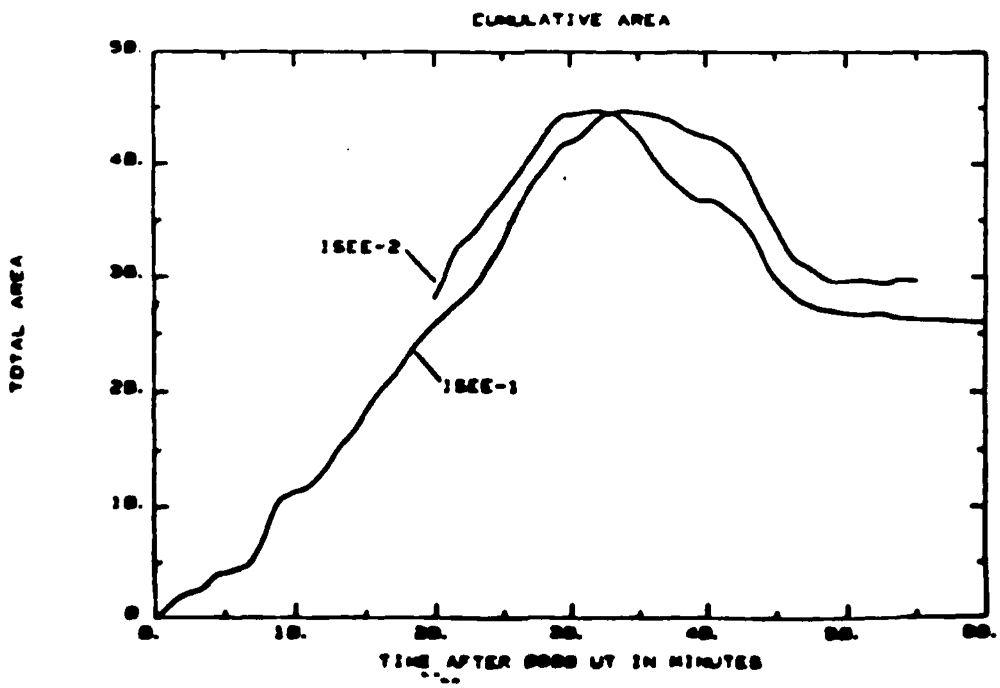
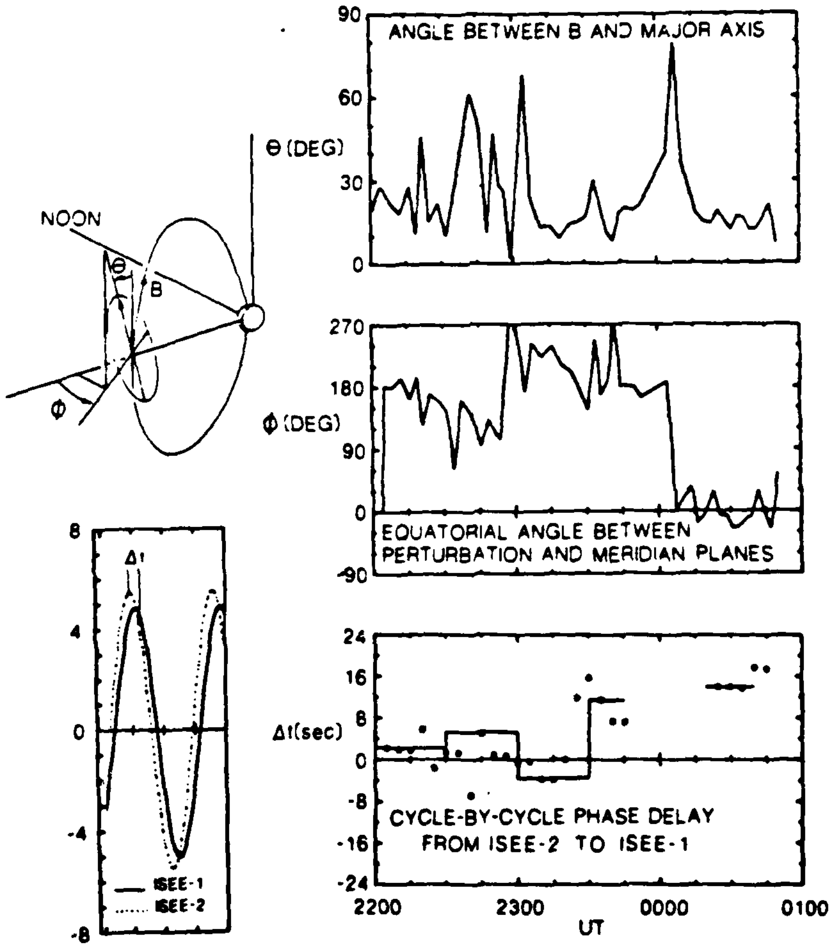

ISEE-1
ISEE-2
AZIMUTHAL COMPONENT
180° PHASE REVERSAL
APPROXIMATELY .4 R_E
TOTAL FIELD
0020-0040 UT


ACCUMULATED AREA AT ISEE-1
TOTAL AREA (NT**2)
50.
40.
30.
20.
10.
0.
0.
10.
20.
30.
40.
50.
60.
UNIVERSAL TIME (MINUTES)
AREA
ANGLE
MAGNITUDE

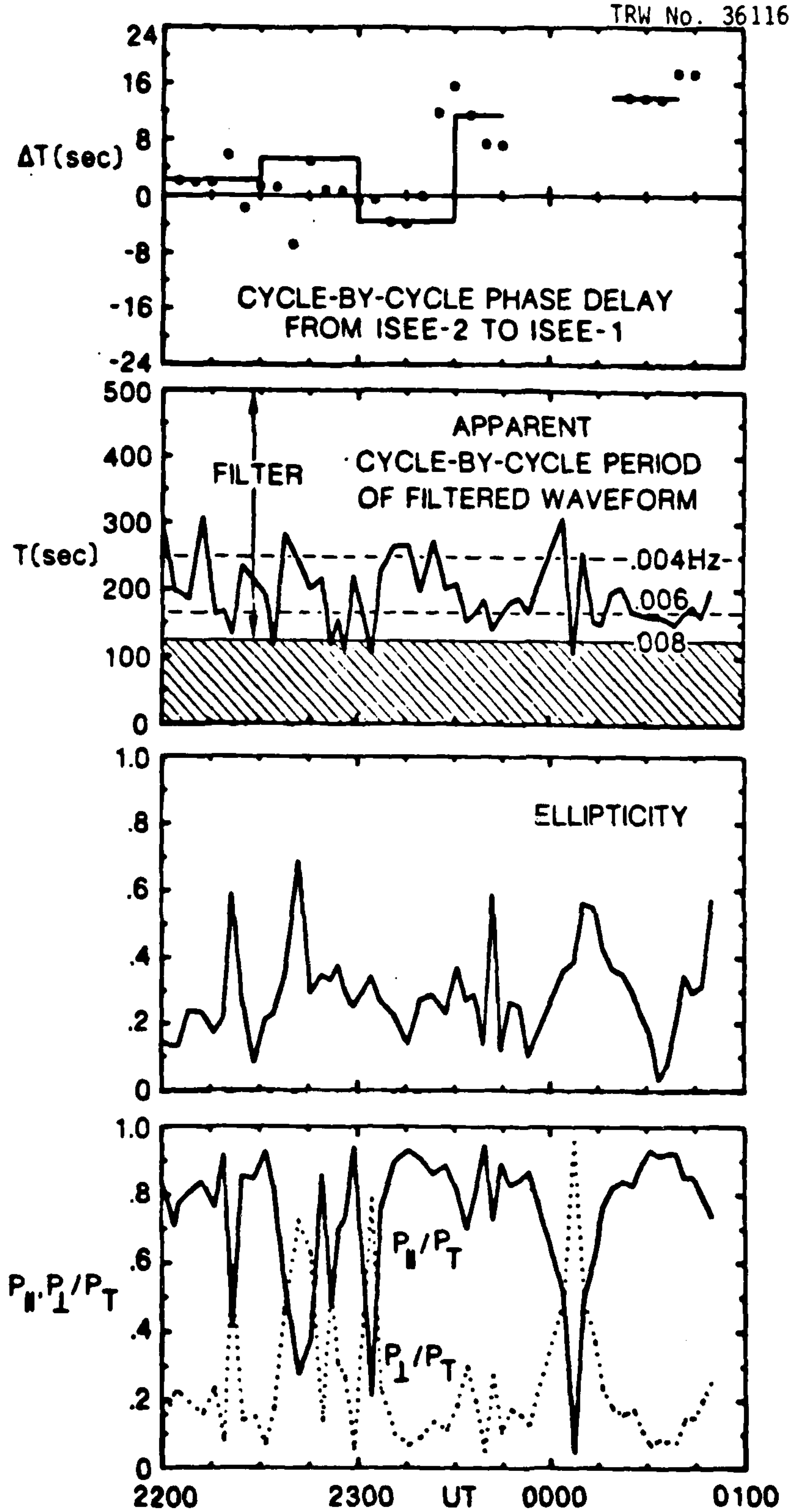

ACCUMULATED AREA AT ISEE-2
TOTAL AREA (NT**2)
20.
10.
0.
-10.
-20.
-30.
0.
10.
20.
30.
40.
50.
60.
UNIVERSAL TIME (MINUTES)
AREA
ANGLE
MAGNITUDE


CUMULATIVE ROTATION ANGLE
5000.
4000.
3000.
2000.
1000.
0
0.
10.
20.
30.
40.
50.
60.
TOTAL ROTATION ANGLE
TIME AFTER 0000 UT IN MINUTES
ISEE-2
ISEE-1


CUMULATIVE AREA
50.
40.
30.
20.
10.
0
0.
10.
20.
30.
40.
50.
60.
TOTAL AREA
TIME AFTER 0000 UT IN MINUTES
ISEE-2
ISEE-1



ANGLE BETWEEN B AND MAJOR AXIS
Θ (DEG)
90
60
30
0
NOON
Θ
B
Φ
270
180
Φ (DEG)
90
0
-90
EQUATORIAL ANGLE BETWEEN
PERTURBATION AND MERIDIAN PLANES
8
4
0
-4
-8
Δt
ISEE-1
ISEE-2
24
16
8
0
-8
-16
-24
Δt(sec)
CYCLE-BY-CYCLE PHASE DELAY
FROM ISEE-2 TO ISEE-1
2200
2300
0000
0100
UT


ΔT(sec)
24
16
8
0
-8
-16
-24
CYCLE-BY-CYCLE PHASE DELAY
FROM ISEE-2 TO ISEE-1
T(sec)
500
400
300
200
100
0
FILTER
APPARENT
CYCLE-BY-CYCLE PERIOD
OF FILTERED WAVEFORM
.004Hz
.006
.008
ELLIPTICITY
1.0
.8
.6
.4
.2
0
$P_\parallel, P_\perp/P_T$
$P_\parallel/P_T$
$P_\perp/P_T$
2200
2300
UT
0000
0100

TRW No. 36116-6006-UT-00

APPENDIX C

TRANSFER OF PULSATION-RELATED WAVE ACTIVITY ACROSS THE MAGNETOPAUSE: OBSERVATIONS OF FAVORABLE CONDITIONS BY ISEE-1 AND 2*

BY

E. W. Greenstadt, Space Sciences Dept., TRW Space & Technology Group

Redondo Beach, California 90278

M. M. Mellott, R. L. McPherron, and C. T. Russell, Institute of Geophysics and Planetary Physics and Department of Earth and Space Sciences University of California, Los Angeles, California 90024

AND

H. J. Singer, and D. J. Knecht, Air Force Geophysics Laboratory

Hanscom AFB, Massachusetts 01731

A variety of loose statistical correlations have long been established between Pc 3,4 and solar wind parameters, indication that these pulsations occur only when conditions prevail. It has also been shown in earlier satellite data that wave power in the magnetosheath varies from sample to sample, but tends to display different rates of decline with frequency above and below the typical proton cyclotron frequency broad spectral peaks for $f < f_p$. No spectron link between wavetrains in the sheath and Pc 3,4 has ever been proved, however, although the possibility that foreshock waves, which resemble pulsations, might be transmitted all the way through the shock, sheath, and magnetosphere to the ground has been asserted, and a model connecting the level and distribution of turbulence in the bow shock and sheath with solar wind parameters has been qualitatively confirmed. The obvious question, regardless of model credibility or broad statistical connections, is whether wave energy is demonstrably transferred or even available for transfer across the magnetopause in any particular case.

We are investigating the properties of waves recorded by the magnetometers of ISEE-1 and -2 when the spacecraft were simultaneously on opposite sides of the day-time magnetopause, a configuration we designate as a "straddle". We have found a few straddles in which power spectra immediately outside the magnetopause could be compared. Particular spectra in the sheath displayed spectral peaks or shape changes between .02 and .06 Hz, while some, but not all, concurrent spectra in the magnetosphere showed peaks within the same frequency range. At the same time, spectra of wave measurements made on the surface at mid-latitude AFGL stations determined that Pc activity was also present within the same frequency band. Power was radiacally reduced, i.e. by half to three orders of magnitude, across the boundary, depending on frequency, but concentration of energy in the Pc 3,4 range stood out in most spectra inside the magnetosphere. There was a visible tendency for power levels to decrease with depth in the magnetosphere, although only by a fraction of the large drop across the magnetopause. The spectral maxima in the magnetosphere do not seem to have represented local resonances.

The results show that when pulsations were present on the ground the magnetosheath was delivering wave energy to the dayside magnetopause over a range of frequencies including Pc 3,4 and that the dayside magnetopause field contained waves in the same range in its outermost region, well beyond the distance at which resonance of the lowest harmonic would have been expected at the observed frequencies.

*Abstract submitted to Chapman Conference on Waves In Magnetospheric Plasmas

TRW No. 36116-6006-UT-00

APPENDIX D

TRANSFER OF PULSATION-RELATED WAVE ACTIVITY ACROSS THE MAGNETOPAUSE: OBSERVATIONS OF CORRESPONDING SPECTRA BY ISEE-1 AND ISEE-2

by

E. W. Greenstadt

Space Sciences Department
TRW Space and Technology Group
Redondo Beach, California 90278

M. M. Mellott, R. L. McPherron, and C. T. Russell

Institute of Geophysics and Planetary Physics
University of California at Los Angeles
Los Angeles, California 90024

H. J. Singer and D. J. Knecht

Plasma, Particles and Fields Branch
Air Force Geophysics Laboratory
Hanscom Air Force Base, Massachusetts 01731

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Bldg R-1, Rm 1176
TRW Space and Technology Group
One Space Park
Redondo Beach, California 90278
(213) 536-2015

TRANSFER OF PULSATION-RELATED WAVE ACTIVITY ACROSS THE MAGNETOPAUSE: OBSERVATIONS OF CORRESPONDING SPECTRA BY ISEE-1 AND ISEE-2

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E. W. Greenstadt

Space Sciences Department
TRW Space and Technology Group, Redondo Beach, California 90278

M. M. Mellott, R. L. McPherron, and C. T. Russell

Institute of Geophysics and Planetary Physics
University of California at Los Angeles, Los Angeles, California 90024

H. J. Singer and D. J. Knecht

Plasma, Particles and Fields Branch
Air Force Geophysics Laboratory, Hanscom Air Force Base, Massachusetts 01731

Abstract. Comparison of power spectra of magnetic field data from ISEE-1 and -2 recorded simultaneously on both sides of the magnetopause showed that power level inside the magnetosphere varied with power level outside in the magnetosheath and suggested that the same frequencies were enhanced on the two sides of the boundary. Power levels were two to three orders of magnitude lower inside than outside the magnetosphere, indicating that wave energy was transmitted inside from the sheath.

INTRODUCTION

A persistent and significant, although weak and disordered, correlation between solar wind properties and daytime geomagnetic pulsation activity in the Pc 3,4,5 range, periods T=10 to 500sec, has been established by many reports, of which we cite a sampling [Bol'shakova and Troitskaya, 1968; Gul'elmi, 1974; Webb and Orr, 1976; Saito et al., 1979; Greenstadt et al., 1979; Wolfe et al., 1980]. These correlations, together with the need to understand pulsaton phenomena in general, have also led to a number of models attempting to explain the observations [Southwood, 1968; Greenstadt, 1972; Vinogradov and Parkhomov, 1974; Chen and Hasegawa, 1974; Kovner, 1976]. Both observation and theory have been concerned with the sources of the waves, the modulation of the waves by the complex media through which they travel, and the control of wave properties directly or indirectly by solar wind conditions. A more comprehensive summary and reference list can be found in a paper by Greenstadt et al. [1980].

Regardless of the specifics of either models or observations, however, there are, in the most general terms, three possible sources of pulsations in the magnetosphere: Waves are produced inside the magnetosphere, waves enter the magnetosphere from the magnetosheath, or waves emanate from the boundary surface separating the magnetosheath and the magnetosphere (i.e. from the magnetopause). None of these possible sources excludes either of the others, but certainly if waves enter the magnetosphere from outside, they must cross the boundary somewhere at some time, and it should be possible to establish by observation a physical similarity between waves detected simultaneously on both sides of the magnetopause. This is the approach we pursue in the present study; the preliminary results reported here support the transfer of wave energy inward from the magnetosheath to the magnetosphere.

We define as a "straddle" a situation in which one spacecraft is on one side of the magnetopause and a second is on the opposite side. The ISEE-1 and -2 satellites provided many such straddle crossings, but we have concentrated on the magnetometer data of 1978, when the spacecraft were separated by hundreds to thousands of km for several months, giving straddles long enough for unequivocal analyses of waves with periods up to several minutes. Our approach is to compute concurrent power spectra on both sides of clearly defined magnetopause crossings and to seek similarities or differences in the spectra from the two spacecraft. We require reasonably continuous data from both satellites over minimal intervals of 15 minutes and preferably much longer. We found four potentially suitable straddles of which we have developed two for this preliminary report, supplemented by two single-spacecraft crossings, as explained later. We present only spectra of the total field magnitude at this time, derived from vector samples every two seconds.

DATA

The two cases we describe occurred on 8 October and 27 November 1978. The 8 October crossing occurred in early afternoon, the 27 November crossing in late morning. The daytime surface field for our cases was measured by the AFGL ground stations in a sector spanning the United States near 55 degrees magnetic latitude. Ground station data processed for this report were recorded by the Newport station at the western edge of the sector, which fell before and after noon during the two intervals of interest, so that the morning-afternoon local times on the ground were reversed from those of our crossings at the magnetopause. We used ground station data as a rough guide to the presence of traditional pulsations on the ground, since it is waves related to the origin of such pulsations that we wish to be studying. The two straddle intervals of this report took place during IMF conditions favorable to the presence of enhanced wave activity in the subsolar magnetosheath convected from quasi-parallel bow shock structure.

Power spectra presented in this study were calculated with the fast Fourier transform. Figure 1 places one spectrum, dotted curve, on the same scales used by Fairfield [1976] to display the characteristics of magnetosheath magnetic noise from several spacecraft. The dotted curve is a power spectrum for the total ambient field recorded by ISEE-1 immediately outside the magnetopause on 8 October. All spectra are for the total field magnitude; details of the earlier spectra can be found in Fairfield's review [op.cit.].

The figure illustrates four principal points: magnetosheath spectra typically show either an enhancement or a slope change, or both, at or below the local proton gyrofrequency (highlighted by the dashed lines); second, magnetosheath spectra are highly variable, both in absolute power level and in the frequencies that might be enhanced in any particular sample; third, spectra taken from ISEE data years later are reasonably representative of the same wave behavior that prevailed during the earlier measurements. Fourth, and most importantly for this report, spectra obtained from ISEE close to the magnetopause do not appear to define a special region in any way unrepresentative of the magnetosheath at other locations.

Figure 2a is an example of our first straddle case. The upper panels of the figure display plots of field magnitude from ISEE-1 and ISEE-2, for the magnetopause crossing of 8 October 1978. ISEE-2, lower field plot, entered the magnetosphere first at 1805:50 and finally at 1813; ISEE-1, top, encountered the magnetosphere later, initially at 1831 and entered finally at 1835:40. Thus, there were 18 minutes during which data were acquired simultaneously from one satellite outside and one inside the magnetopause.

Spectrum A shows the wave power in the total field in the magnetosheath just outside the magnetopause, at ISEE-1. The next spectrum below, B, shows the wave power in the magnetosphere just inside the magnetopause, at ISEE-2, for the same time interval as that of the first spectrum. The power was appreciably lower and the decrease in power with frequency clearly much steeper inside than outside the magnetopause, beginning with about one third the outside power at the lowest frequencies. At 0.1 Hz, there were three orders of magnitude difference between the two spectra.

Spectrum C, at bottom, represents the power on the ground at the AFGL station at Newport, Washington, for the same intervals as in the depicted satellite samples. The ground station was a few hours west of the satellites, about local noon. The shaded vertical stripe in the spectral panels draw attention to the enhancements in power at the satellites and on the ground that appear to bind wave activity together in the inner magnetosheath, the outermost magnetosphere, and at the earth's surface. All the spectra show some concentration of power between .02 and .07 Hz in the form of a plateau or peaks in the respective curves.

Figure 2a shows a progressive decline in power from the magnetosheath to the earth's surface. Each spectral curve is contained in, i.e. accounts for a fraction of the power of, the next spectrum above it. The magnetospheric spectra are well below that of the magnetosheath and are closer to one another than to the latter, the discrepancy being greatest at the highest frequencies.

Figure 2b superposes spectra from a second straddle case on 27 November 1978, when ISEE-1 was just outside the magnetopause. ISEE-2 was deeper inside the magnetosphere, having entered at 2000 UT, than it had been on 8 Oct., and the Newport station was below and east of the satellite meridian (in the early afternoon sector). In this instance, the power in the sheath (A) displayed enhancement and a plateau between .011 and .05 Hz, as did also the power in the magnetosphere (B), while the corresponding power on the ground (C) was relativily featureless, but essentially at the same level as at ISEE-2. Whether the apparent lack of frequency enhancement on the ground at this time was because of a delayed effect not yet visible, an unfavorable position in the afternoon sector, or a poor choice of representation of the surface record is still to be determined. The small graph at the bottom shows the power distribution in By at Newport for the local noon and afternoon interval including the 22-minute segment of the upper graph; clearly, there was some activity in the surface field within the longer interval and within the enhanced portion of the spectrum at the satellites. The attenuation of wave power across the magnetopause is obvious here, as in the previous case, but we also see that the frequency range of enhancement was shifted to somewhat lower frequencies, in all locations, than in the case of 8 October, as indicated by the shading in Figure 2.

The magnetosheath spectra of 8 Oct. and 27 Nov. are superposed in Fig. 3, showing that the power of the 27 Nov. spectrum peaked at lower frequency and dropped more rapidely than the power on 8 Oct. This difference corresponds to the slightly different regions of the frequency scale that seemed to be show enhanced power in the magnosphere, as shaded in Figure 2 . Unfortunately, the absolute power levels in the magnetosheath in the two cases examined above did not differ appreciably from each other, considering the wide range of power exhibited in the curves of Figure 1. In order to study whether power inside the magnetosphere is related generally to power in the magnetosheath, it was necessary to examine nonstraddle cases. On the premise that the sheath spectrum remained substantially unchanged from one interval to the next over an hour's time, we selected cases with significantly different power levels and compared spectra before and after magnetopause crossing, rather than simultaneous spectra on opposite sides of the boundary. Corresponding magnetosheath and magnetosphere spectra are superposed in Figure 4 for three days, 8 October, and 10 and 17 September 1978. The 8 October curves are already familiar. The new ones show that progressively lower power in the sheath corresponded to progressively lower power in the magnetosphere, suggesting, with these few cases and the necessary assumption of stationarity on the 10th and 17th, that the powers inside and outside the magnetopause were directly related.

SUMMARY

The data presented above may be summarized as follows, with the understanding that we refer essentially to the frequency range 0.01 < f < 0.1 Hz (periods 10 < T < 100 sec.):

The power within the magnetosheath was 10 to 1000 times the power in the magnetosphere;

The power within the magnetosphere varied less than a factor of 10 from the magnetopause to the surface;

The power level inside the magnetosphere correlated overall with power level outside the magnetopause;

The frequency of power enhancement in the magnetosphere appeared to shift with the frequency of power enhancement in the magnetosheath.

The power outside the magnetopause appeared to be representative of power in the magnetosheath generally.

In addition to the foregoing, we have found evidence that the variable presence of a frequency range of enhanced power in the magnetosheath was correlated with the variable presence of an IMF orientation favorable to the occurrence of quasi-parallel structure in the bow shock around the subsolar point. This result will be treated in a separate report.

DISCUSSION

Similarity between spectra in the magnetosheath and magnetosphere may be explained, excluding coincidence, in the three ways defined in the INTRODUCTION. The observations listed in the SUMMARY suggest that internal magnetospheric origin may be excluded from consideration because of the higher power observed outside the boundary. Moreover, a principal criterion by which we selected cases was the appearance of a clear magnetopause allowing us easily to determine that one spacecraft was inside, the other outside the boundary. This would eliminate wave propagation outward along field lines locally interconnecting the solar wind to the magnetosphere. In fact, we have established that in one case the boundary was well approximated by a tangential discontinuity.

Surface waves are an unlikely explanation because of the overwhelming power in the magnetosheath compared to the magnetosphere. The newest calculations of surface wave effects [Pu and Kivelson, 1983] require that the magnetic wave power inside the boundary exceed that outside, opposite our results. Also, the frequencies expected for surface waves tend to be lower than those with which we have been dealing.

We conclude therefore that our preliminary results are consistent with external wave origin, specifically with the transfer of a small fraction of magnetosheath wave power, possibly derived from quasi-parallel shock structure, into the magnetosphere to appear as waves in the Pc 3-4 range.

The asserted commonality of frequency enhancement across the boundary, as illustrated here in Figure 2, is subtle at best. This is hardly surprising, since we are dealing with a global phenomenon notoriously elusive to sharply defined correlations, which we chance to sample as a few straddles at a few points in space. We chose the two examples here as the purest straddle cases. Other spectra, with more persuasive enhancement profiles, were obtained in data contexts requiring more exposition than could be included in this letter and will be the subject of a separate report. The component-by-component details of the transfer process, the global picture describing where the most effective transfer takes place, and the pathways whereby broadband energy in the magnetosheath is recorded as monochromatic pulsations in the magnetosphere remain to be determined.

Acknowledgements. Support for this report was provided by USAF contract F49620-81-C-0063 and NASA contract NASW-3690 (at TRW); NASA Grant NAS5-25772 (at UCLA).

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FIGURE CAPTIONS

Figure 1. An ISEE-1 magnetosheath spectrum obtained near the magnetopause (dots), superposed on a selection af spectra from earlier spacecraft in the magnetosheath.

Figure 2. Magnetic field magnitude records and superposed spectra for two cases of ISEE-1, ISEE-2 straddles of the magnetopause: (a) 8 Oct., (b) 27 Nov., 1978; A, B, and C signify spectra for the indicated intervals at ISEE-1, ISEE-2, and the AFGL Newport ground station. The insert at bottom right covers a longer interval at Newport, as noted.

Figure 3. Superposed magnetosheath spectra from 8 Oct. and 27 Nov.

Figure 4. Superposed power spectra for three different power levels in the magnetosheath and magnetosphere on three different days.

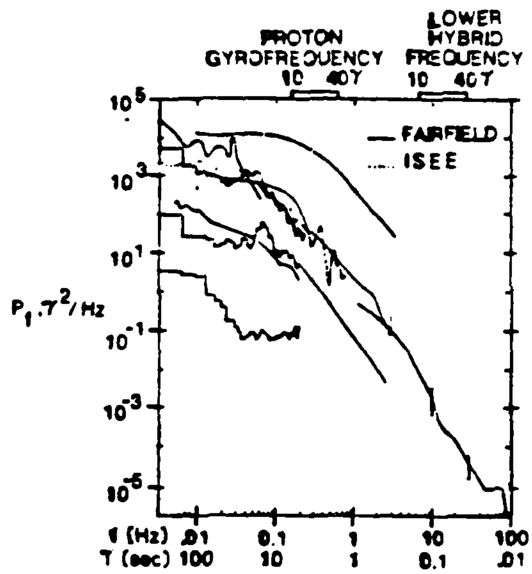

Figure 1. An ISEE-1 magnetosheath spectrum obtained near the magnetopause (dots), superposed on a selection of spectra from earlier spacecraft in the magnetosheath.

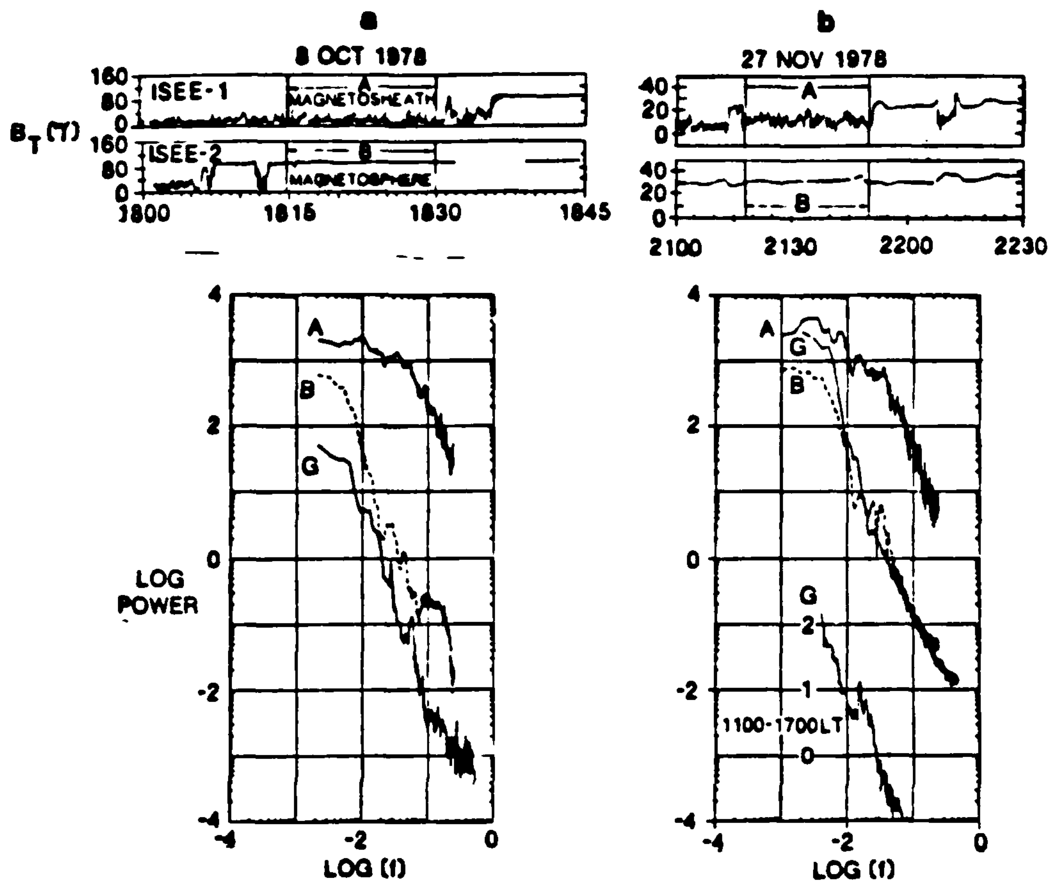

Figure 2. Magnetic field magnitude records and superposed spectra for two cases of ISEE-1, ISEE-2 straddles of the magnetopause: (a) 8 Oct., (b) 27 Nov., 1978; A, B, and G signify spectra for the indicated intervals at ISEE-1, ISEE-2, and the AFGL Newport ground station. The insert at bottom right covers a longer interval at Newport, as noted.

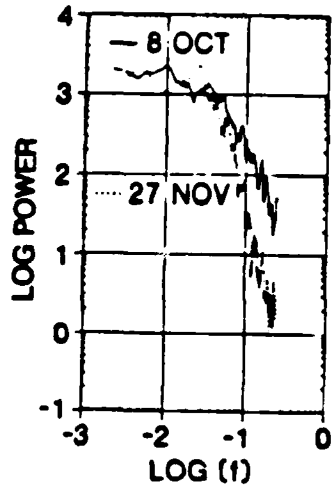

Figure 3. Superposed magnetosheath spectra from 8 Oct. and 27 Nov.

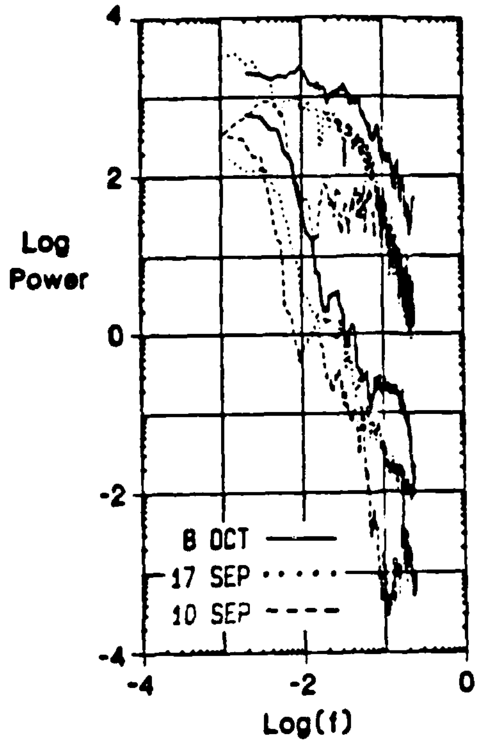

Figure 4. Superposed power spectra for three different power levels in the magnetosheath and magnetosphere on three different days.

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APPENDIX E TRW No. 36116-6006-UT-00

LARGE-AMPLITUDE MAGNETIC VARIATIONS IN QUASI-PARALLEL SHOCKS: CORRELATION LENGTHS MEASURED BY ISEE 1 AND 2

E. W. Greenstadt

Space Sciences Department
TRW Space and Technology Group
Redondo Beach, California 90278

M. M. Hoppe

C. T. Russell

Institute of Geophysics and Planetary Physics
University of California at Los Angeles
Los Angeles, California 90024

Abstract. Wide separations up to more than 1 R_E between ISEE 1 and 2 during the second half of 1978 have been used to measure the correlation length of magnetic pulsations in quasi-parallel shocks. When the two spacecraft were less than a few hundred km apart, magnetic oscillations measured by magnetometers on both spacecraft exhibited virtually identical waveforms, but at distances of several thousand km, the two time series of field variation showed no detailed similarity at all. The correlation coefficients of the pulsations dropped from close to 1.0 for spacecraft separations of less than 100 km to 0.2 for separations of greater than 800 km. A correlation length of several hundred km may be related to the gyroradius of return protons with energy typical of the peaks of diffuse and beam ion distributions.

Introduction

Simultaneous measurements by two or more instruments at different locations within the Earth's bow shock and foreshock regions constitute the essential tool for distinguishing temporally from spatially varying structures. So far, analysis of data from the satellite pair ISEE 1 and 2 has emphasized the mutual consistency of their measurements. Indeed, one of the striking features of the earliest data from the magnetometers of ISEE 1 and 2 was the detailed similarity, under normal conditions, of wavetrains at the two vehicles even in the highly-irregular, large-amplitude perturbations of the quasi-parallel shock, of which examples are shown in this report. A high β, of course, even the quasi-perpendicular profile differs from one spacecraft to the other [Russell and Greenstadt, 1979]. Signal correlation, because of its obvious application to timing the motions of waves and boundaries between the satellites, has therefore received much attention, and, in fact, one study has successfully defined propagation vectors and velocities of ULF waves in the foreshock [Hoppe and Russell, 1980; Hoppe et al., 1981]. The limits of correlation are equally of interest, however.

In contrast to most of the early data from the ISEE project, which were obtained when the satellites were close together (i.e., within a few hundred km of each other), the data from the second half of 1978 offer the first opportunity to examine directly the extent of signal correlation, hence spatial variation, in the local plasma environment when the two spacecraft passed through bow shock distances at varying separations up to several thousand km. This report presents the first documented change of correlation with distance for a magnetic constituent of the shock structure and discusses a possible relationship of correlation length to ion gyroradius. Our examples are all quasi-parallel, by which we mean the angle between the interplanetary magnetic field and the local model shock normal was less than about 50° and large-amplitude field oscillations were recorded.

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Variable Correlation

Figure 1 offers a visual display of the variations in wave correlation observable in the running 12-second averages (plotted every four seconds) between ISEE 1 and ISEE 2. In 1(a), the two traces of magnetic-field magnitude exhibit almost identical waveforms. Moreover, the similarities of changing field pattern occurred in both the ULF foreshock waves (e.g., around 0015 and 0030) and in the larger-amplitude waves and pulses defining the outer edges of the quasi-parallel shock structure, as seen between 0020 and 0024. The fidelity of wave duplication at the two spacecraft persists at higher resolution, illustrated in Figure 2, where we see unaveraged data with samples recorded every 0.25 second. A segment of the data from Figure 1(a) is shown in Figure 2(a). While not identical in every detail, or exactly alike in amplitude, the two waveforms shared essentially the same pattern for periods of a few seconds or longer, and the occurrence of higher-frequency bursts was almost simultaneous at both satellites in the illustrated examples. Figure 2(b) is an overlay of ISEE 1 and ISEE 2 data for a section of 2(a), showing clearly the close similarity of the two signals, albeit with slightly variable delay from one satellite to the other.

Returning to Figure 1, we note that in 1(b) the similarity of the two field plots is considerably less pronounced than in 1(a). Indeed,

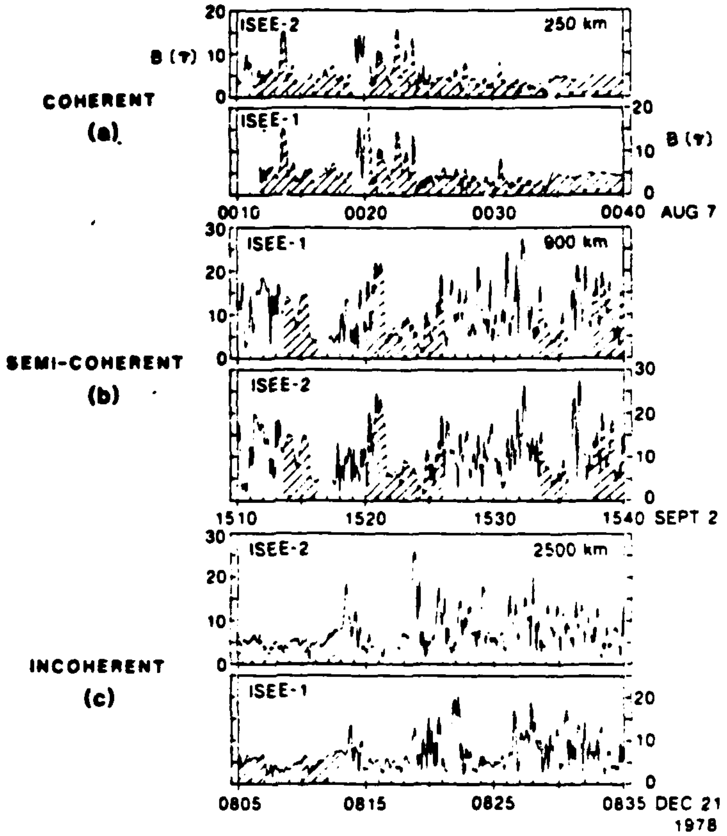

Fig. 1. Three cases showing the decrease in coherence with increasing separation between ISEE 1 and 2. Shading indicates intervals of similar waveform.

there are only limited sections, shaded for emphasis, where we would assert the credibility of such a correlation on the strength of pattern inspection alone. In Figure 1(c), an interval is shown in which there appears to have been still less correlation between the waveforms at the two spacecraft than in case 1(b). In particular, while sections of similar patterns persisted among the smaller, foreshock waves (shading), the larger-amplitude pulsations have visibly lost any sign of correspondence outside of their simple joint occurrence. Certainly, the contrast between 1(c) and the pervasive waveform reproduction of 1(a) is clear. Overall, then, Figure 1 illustrates the range of variability of waveform correlation recorded in the quasi-parallel shock and foreshock.

Decrease of Correlation With Distance

In each of the pairs of panels of Figure 1, at the upper right, is printed the distance, 250, 900, or 2300 km between ISEE 1 and ISEE 2. Clearly, the separation in 1(c) was ten times that in 1(a). This implication has been made more quantitative by computing cross-correlation coefficients for 20 pairs of such cases in which the upstream β ranged from 0.7 to 3.0, the solar wind Mach number from 5.0 to 6.5, and the local normal angle from 10° to $\geq$45°.

Correlation coefficients averaged over four-minute intervals were calculated for successive 0.25-sec lags, consistent with the magnetometer's acquisition rate of four vectors per second. The correlation coefficient present in this report is that of the average lagged product of the time series on the two spacecraft for each of the three vector components weighted by the variance in that component. Further details can be found in the paper by Hoppe and Russell [1980].

Figure 3 is a plot of the cross-correlation coefficients of large-amplitude, quasi-parallel shock pulsations for the 20 cases, at spacecraft-separation distances ranging from 105 to 5,700 km. The graph demonstrates the fall-off of pulse correlation with distance, showing nearly perfect correlation at the left and nearly complete lack of correlation at the right. We have not regarded the preliminary data of Figure 3 as sufficiently refined to justify fitting the points with an exponential or other heuristic model; we infer, tentatively, that the correlation remains high, but declines progressively with separation up to several hundred km, then drops rapidly to essentially no correlation at a threshold distance of about 1,000 km. One argument against reading the length scale too carefully at this stage is the unknown role that gross motion of the whole shock may have played in the data set. We may hope that any such effect would have averaged out over many examples where the shock moved both in and out. A reliable assessment of shock motion by two satellites inside the quasi-parallel structure, a prerequisite configuration for a correlation study, is naturally precluded. The figure suggests, then, that the outermost part of the quasi-parallel shock pulsations occur in fairly well-marked "cells" containing magnetic fluctuations of common origin, distinguishable from fluctuations in adjacent cells. We can call the cell dimension of about 1,000 km the "correlation length" of the pulsations.

We may imagine that a progressive decline of correlation occurs when a major wave component is damped with distance, so that its contribution is large at one spacecraft but inconspicuous at the other. While dissipation of wave energy with distance may take place, there is little indication that this effect is responsible for much of the observed variation in correlation. Corresponding sections of data at intermediate distances, as in Figure 1(b), for example, show no consistent amplitude difference from one observation point to another, and some of the correlation that does persist at longer distances, as in Figure 1(c), occurs in the smaller waves, which appear to retain their amplitudes very well [in the example of Figure 1(c), ISEE 1 was almost directly downstream from ISEE 2]. Thus, simple wave damping appears inadequate as an explanation for loss of correlation, especially the major loss at the edge of a "cell", and we need an alternative explanation.

Possible Relation To Return Particle Populations

We may also imagine that the bulk of an observed pulse train is produced by currents from an identifiable sub-population of particles such as return ions -- i.e., reflected or back-streaming ions [Gosling et al., 1978; Eastman et al., 1981; Sentman et al., 1981; Bonifazi and Moreno, 1981] -- in a region occupied by those particles. When both magnetometers are in the same region, they record the same wavetrain; when they are not, each records a wavetrain dominated by local currents but superposed on components propagated and/or convected from other regions upstream.

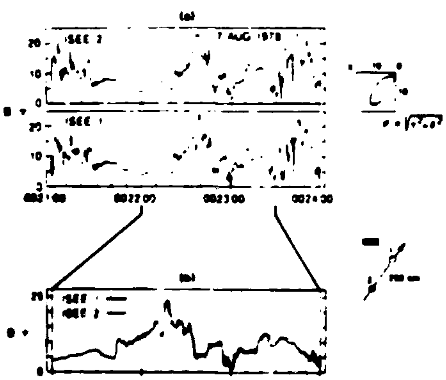

Fig. 2. Details of well-correlated pulsations shown in Figure 1(a). Inserts illustrate position of satellites and orientation of separation vector.

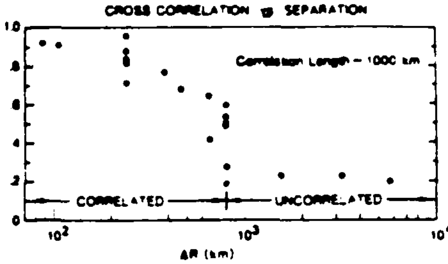

Fig. 3. Cross-correlation vs separation distance ΔR.

According to this alternative explanation, the "correlation length" should be related to some characteristic particle-current dimension peculiar to the shock or foreshock, and this seems to be the case. In Figure 4, we reproduce the distributions of bulk and thermal velocities for the recognized categories of return (back-streaming) ions, which we know are present just outside the shock, as plotted by Bonifazi and Moreno [1981]. Treating these distributions as if they were representative of velocities perpendicular to the ambient field, we have added scales of equivalent Larmor radii at the bottom, using an average IMF of 5 γ. We see at once that, regardless of category, virtually all the measured velocities would correspond to gyroradii below about 2000 km. Moreover, the peaks of the distributions of diffuse-ion bulk velocity (at left) and reflected-ion thermal velocity (at right) occur at a few hundred km, where correlation is high in Figure 3. It is not unreasonable, then, that wave shapes are shared in regions occupied by associated return ions circulating around the local ambient field. The gyrophase-bunched ions described by Eastman et al. [1981] and Gurgiolo et al. [1981] come readily to mind.

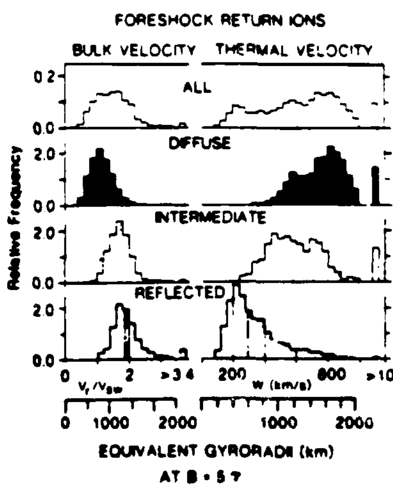

Fig. 4. Equivalent gyroradii of return ions studied by Bonifazi and Moreno (1981). In the original graphs, just above the gyroradii scales, symbols V_r/V_{sw} and W denote the ratio of return ion velocity to solar wind velocity (left) and return ion thermal speed (right).

Discussion

We have displayed our quantitative analysis for a few cases of the larger "pulsations" of the quasi-parallel shock under typical plasma conditions ($\beta \approx 1$, $M \approx 5$) and plotted the results against the straight-line distances separating the two spacecraft. The visual evidence in Figure 1(c), supported by additional cases not shown here, suggests that the smaller, foreshock waves retain their patterns better at large separation than do the pulsations. Clearly, a quantitative result pertaining to foreshock waves will be more difficult to achieve, since the total separation of the two satellites in the foreshock did not exceed about 7,000 km, which could be commensurate with, if not shorter than, the smaller waves' correlation length. Moreover, the correlation length may depend not on simple separation distance, but on distance along the ambient field, along the guiding center backstreaming direction, along the wave propagation vector, or along or across the solar wind flow. We have plotted correlation vs separation projected on the local shock normal and found a decline similar to that in Figure 3. We have also found that in all cases examined so far, the lag has always been from the spacecraft ahead in the solar wind to the one downwind. Numerous cases will have to be found, and extensive analysis done, to distinguish these possibilities reliably and to verify and understand the downwind delay in relation to particle behavior. We note, however, that a correlation length shorter for the large pulsations than for the upstream waves is compatible with the Larmor radii association mentioned above, as follows:

Recall that the distance scales at the bottom of Figure 4 were derived using an IMF magnitude of 5γ, since this is the average where the upstream distributions are found; but where quasi-parallel pulsations occur, the average *field is often double the average nearby IMF.* If the radius scales of Figure 4 were redrawn using a field of 10γ, the ion distributions would be concentrated at distances half those shown, implying very strong current and wave correlation at short separations, as documented in this report. Thus, small correlation lengths for the large waves and larger correlation lengths for the small waves argue for wave creation by identifiable groups, or beams, of return ions in regions measured by the appropriate gyroradii. Of course, the very long, actual correlation lengths of waves in the foreshock probably include the influence of convection by the fast, unshocked solar wind.

Foreshock ions already released from the shock and returned to the solar wind cannot fully represent the ions responsible for the correlation cells discovered here. While ions *composing the foreshock return* particles are doubtless also present in the outer edge of the quasi-parallel structure [Asbridge et al., 1978], an important measurement still to be reported is the spectrum of trapped, or "second distribution", ions in the quasi-parallel pulsation structure itself. These should replace the spectra used in Figure 4. From such a spectrum, a more pertinent range of gyroradii can be inferred. We may then ask whether the quasi-parallel shock contributes its own identifiable seed distribution to the ions of the foreshock or whether the missing distributions are simply foreshock particles blown downstream. It is unclear at present how energetic ions derived entirely from upstream scatter of reflected ion beams [Bame et al., 1980] would retain or recover a sharply defined cell dimension on reentering the shock, but the alternative postulate that dispersed ion distributions are produced primarily by direct sources at or near the bow shock [Eastman et al., 1981] awaits systematic verification. Hopefully, detailed investigation of the ions themselves will contribute complementary information to the study of wave-particle interactions in the shock and foreshock, facilitated by the wide separations of the ISEE 1 and 2 spacecraft in 1978.

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